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Performance-Related Specifications for Asphalt Concrete—Phase II

U.S. Department of Transportation
Federal Highway Administration

Research and Development
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FOREWORD

This report presents the results of a study to further the development of performance-related specifications for hot mix asphalt pavement construction. Laboratory testing was conducted to develop relationships between materials and construction variables, e.g., asphalt content and compaction level, and fundamental mixture properties, e.g., resilient modulus and tensile strength. Some of the resulting models are coupled with existing relationships between mixture properties and pavement performance in a computerized spreadsheet version of a conceptual performance-related specification system. The equations and computer program can be used in simulations and to assist in generating pay adjustment plans. This report will be of interest to engineers concerned with quality assurance, specifications, and construction of hot mix asphalt pavements.

Sufficient copies of this report are being distributed to provide two copies to each FHWA regional office and three copies to each FHWA division office and each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

James D. Cooper
Acting Director, Office of Engineering and
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NOTICE

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16. Abstract

The objective of this study was to further the development of performance-related specifications (PRS) for asphalt pavement construction by: (1) conducting laboratory studies of the relationships between materials and construction (M&C) variables and fundamental response variables, and the relationships between the fundamental response variables and pavement performance indicators; and (2) developing a detailed plan (experimental design, construction details, and data collection and analysis) for an accelerated field test at a test track facility.

The laboratory study performed for this research project focused on the development of secondary prediction relationships, which are equations that establish the relationship between M&C variables and fundamental response variables. The results of the laboratory study indicate that compaction level had more influence on mixture properties than any other variable in the experiment. A technique for estimating compaction effects using measurable specimen properties was found and resulted in a compaction index equation. The prediction equations can be used with an estimated compaction index to relate measured mixture properties to optimum properties. These equations can also be used to predict relative effects of proposed changes in materials and construction specifications on performance-related mixture properties. When used with equations that relate performance-related mixture properties to pavement performance, the equations derived in this study can be used to establish penalties for nonconformance to specification limits. An automated version (LOTUS 1-2-3, Spreadsheet) of the conceptual PRS system is included.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER 1. INTRODUCTION

BACKGROUND

Over the past 10 or 12 years, considerable research has been directed towards the development of performance-related specifications for measures of materials and construction (M&C) quality. In 1976, an NCHRP synthesis was published on statistically oriented end-result specifications.[1] Fundamental concepts for performance-based acceptance plans and associated price-adjustment systems were reported in the late 1970's and many further developments were reported in the early 1980's. (References 2 through 8, for example.)

A state-of-the-art for flexible pavement specifications was published by the Federal Highway Administration (FHWA) in 1984.[9] At about the same time, a research program for development of performance-related specifications was instituted by the National Cooperative Highway Research Program (NCHRP), beginning with NCHRP project 10-26. The main objective for project 10-26 was to identify variables and existing data bases from which appropriate relationships between M&C factors and performance indicators might be derived as inputs for specification system development. It was concluded that this subject area was very important, but, that existing data bases were probably inadequate for direct derivation of the essential relationships.[10]

As a consequence of the project 10-26 study, the NCHRP decided that further research on performance-related specifications should be within a general framework that provided for multistage derivation of the needed relationships. In this framework, primary prediction relationships would be between performance indicators (e.g., distress levels or applications to "failure") and known performance predictors (e.g., surfacing thickness and mechanistic properties). Secondary prediction relationships, on the other hand, would show the nature and extent of associations among the performance predictors and other M&C factors that are amenable to M&C control (e.g., asphalt concrete (AC) or portland cement concrete (PCC) mix factors).

Under this new approach, NCHRP project 10-26A was initiated in 1986 and was completed in 1990. The research report covered several aspects of performance-related specifications (PRS) development for AC materials and construction, including experimental results from laboratory studies and algorithmic demonstrations of particular M&C acceptance plans and payment schedules.

In 1987, the FHWA embarked on a multi-million dollar program for the development of PRS for both AC and PCC pavements. The first project was designed to provide a research program for PCC pavements parallel to the NCHRP 10-26A study.[11] A project to further the results from the first project is currently (1991) underway.

The basis for development of the PRS in both the current NCHRP-AC and FHWA-PCC projects is the conceptual framework laid out in reference 12. A general framework for specifications development is given in chapter 2.

One of the most important elements of this development process is the availability of secondary prediction relationships that can be used to relate M&C factors (such as asphalt content, grade, etc.) to the pertinent explicit predictors (such as asphalt concrete modulus) found in the various primary prediction relationships. Unfortunately, most of the existing models suffer fundamental shortcomings that limit their usefulness in PRS development. As identified in the NCHRP-AC and FHWA-PCC reports, these shortcomings include:[11,13]

- The models are limited to target values for the M&C variables and, therefore, cannot account for the effects of M&C nonconformance.
- The models are often limited to a narrow range of mixture characteristics, thus, extrapolation to a wide range of mixture behaviors is inappropriate.
- Most models do not consider all potential M&C factors, nor do they address the effects of interaction among factors.
- Most models do not reflect any pertinent statistical measures of error/precision (i.e., coefficient of determination, standard error of estimate and/or number of observations).

Another key element of the PRS development process is the availability of comprehensive primary prediction relationships. In general, existing primary prediction relationships are suitable for PRS development; however, it is highly desirable to verify and/or enhance these relationships through well-planned laboratory and field test programs. Furthermore, it is also desirable to develop new relationships (or improve existing ones) to account for the effects that some M&C factors have on performance that are not necessarily reflected in the explicit predictors. Examples of such M&C factors include:

- Aggregate type.
- Sulfur extended asphalt.
- Rubber asphalt.
- Fabric/grid reinforced asphalt concrete.

Recognition of the need for better primary and secondary relationships for use in PRS development is the reason for the study addressed in this report.

OBJECTIVES

The primary objectives of this study are to continue development of performance-related specifications for asphalt concrete pavement construction by:

- Conducting laboratory studies of the relationships between materials and construction variables and fundamental response variables, and the relationships between the fundamental response variables and pavement performance indicators.

- Developing a detailed plan (experimental design, construction details, and data collection and analysis) for an accelerated field test at a test track facility.

SCOPE OF WORK

This research study furthers the development of PRS for construction of AC pavements. The scope of work consists of developing a detailed experiment design for a laboratory study, conducting the laboratory study (following approval of the plan), and developing a detailed plan for an accelerated field test of selected pavement sections. The field test efforts of this study shall be coordinated with those of Strategic Highway Research Program (SHRP) researchers in the technical area of asphalt-aggregate systems. The end products of this study shall be the following:

- A complete, though not necessarily fully verified, set of relationships between M&C test results and the expected performance of asphalt concrete pavements.

- A detailed plan for an accelerated field test to confirm and extend the above relationships.

Throughout the scope and work of this study, special efforts have been made to draw upon and ensure compatibility with relevant results from all cited developments of performance-related M&C specifications.

CHAPTER 2. FRAMEWORK FOR DEVELOPMENT OF PERFORMANCE-RELATED M&C SPECIFICATIONS

A general framework for the development of performance-related M&C specifications is shown schematically in figure 1. The framework is based on concepts that were presented in reference 12 and is consistent with the framework that has been developed in NCHRP project 10-26A for AC pavement specifications and an FHWA contract for PCC pavement specifications.[11,13]

Shown at the left of figure 1 are four sets of relationships (R1 through R4) and two boxes (B and C) that represent variables contained in the relationships. Box A represents data bases for all variables that are used to derive the relationships, including variables in box B and box C.

The right side of the figure shows four types of additional inputs (boxes D through G) to algorithms (R5) that are used to produce the performance-related M&C specifications represented by box H.

In this chapter, an overview is given for all 13 framework elements.

Primary relationships are defined to be those for predicting pavement stress (R1), pavement distress (R2), and pavement performance (R3) from particular combinations of predictors (box B) that represent traffic, environmental, roadbed and structural conditions. It is assumed that any relationship among R1 through R3 is an equation (or algorithm) that predicts values for an output variable that is a specific indicator of stress, distress or performance. One stress indicator, for example, might be a particular strain in the AC surfacing layer, one distress indicator might be inches of wheelpath rutting per mile, and one performance indicator might be the number of equivalent single axle loads (ESAL's) at which the pavement's serviceability index (PSI) has reached 2.0.

Predictor variables represented by box B are well-defined independent variables that appear explicitly in one or another of the primary relationships. Examples are surfacing thickness (box B4), roadbed soil modulus (box B3), annual precipitation (box B2), and annual rate of equivalent single axle load accumulation (box B1).

A number of specific primary relationships for AC pavements have been developed from past research. In general, each has been derived either from mechanistic considerations (M in figure 1), from empirical models (E) or from some combination of the two methods (ME). A fourth method for deriving a particular relationship is through algebraic manipulation (A) of one or more relationships that were derived via methods M, E or ME.

As indicated in box A, data bases used to derive primary relationships may be either observational, experimental or some combination thereof. An observational data base, for example, might represent observations from a set of selected highway construction projects. An experimental data base might arise from a designed study in which control is planned and exercised over the independent variables of the study. Thus, experimental data bases can result from sets of specially constructed test sections as in the American Association of State Highway Officials (AASHO) Road Test, or from the test specimens of a designed laboratory experiment.

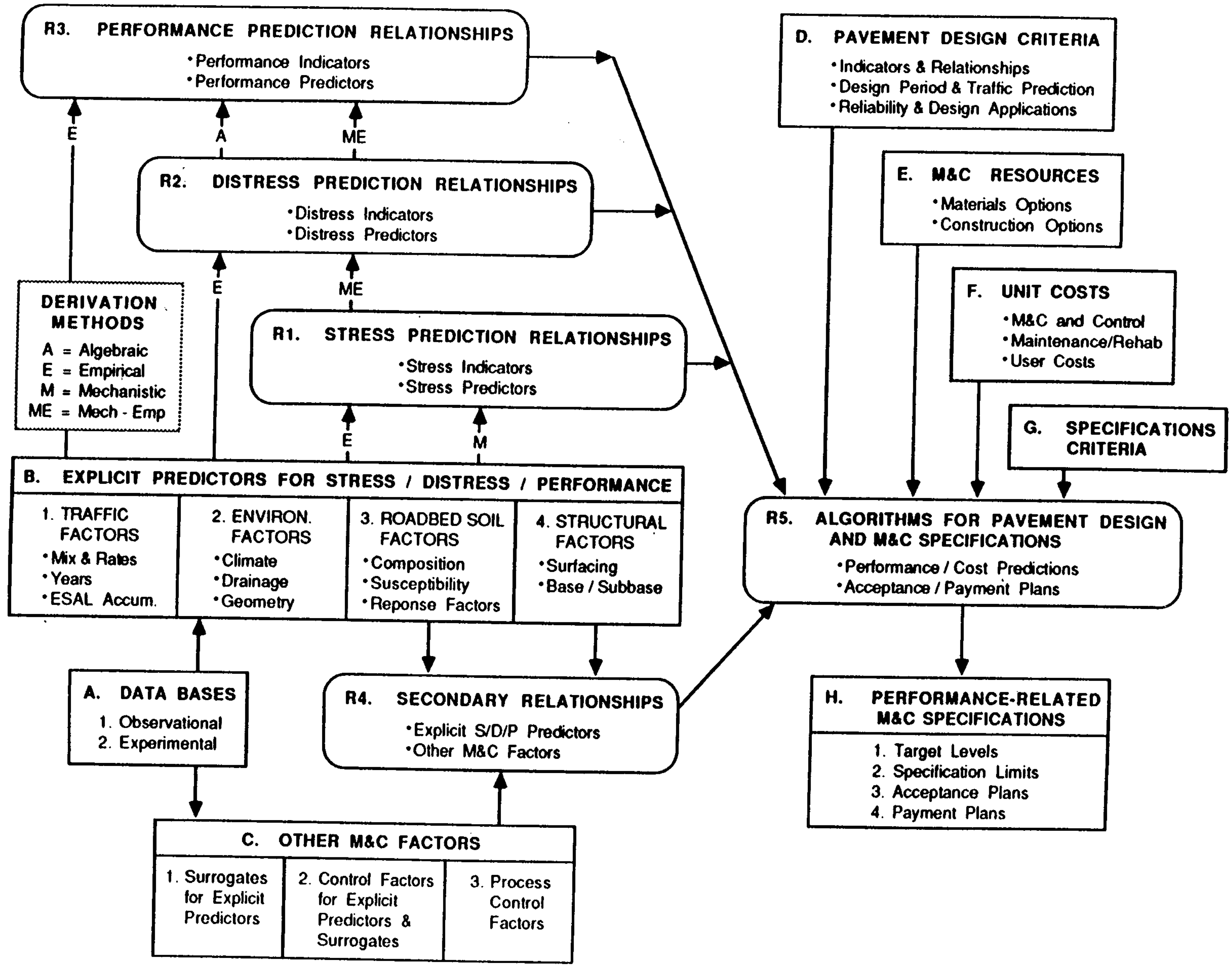


Figure 1. Framework for development of performance-related materials and construction (M&C) specifications.

Associated with every prediction relationship is at least one statistical distribution of prediction errors, i.e., differences between predicted values for a given indicator and corresponding observed values of the indicator. Characteristics of the error distribution (e.g., shape, mean value, standard deviation) are, therefore, needed for the development of performance-related M&C specifications.

Certain explicit predictors in boxes B3 and B4 may be materials and/or construction factors whose levels are controlled directly during the M&C process (e.g., layer thicknesses). In other cases, explicit predictors may be controlled indirectly through other M&C factors that are represented by box C. All M&C factors that are not explicit predictors for a particular set of relationships fall in one or another of three classes of "other" M&C factors.

Class C1 contains factors that are not explicit predictors but that may be used as surrogates for factors that appear in one or another of R1 through R3. For example, the relationships in use may contain AC stiffness as an explicit predictor, whereas AC tensile strength might be controlled through M&C specifications. In this case, tensile strength is a surrogate for stiffness.

Class C2 contains M&C factors that are not explicit predictors but have specifications to provide indirect control for explicit predictors or their surrogates. If, for example, a prediction relationship contains modulus of subgrade reaction as an explicit predictor of stress/distress/performance, then class C2 may contain factors, such as density and compaction, whose specifications provide at least partial control over soil modulus. Other examples of factors in class C2 are those which specify certain AC mix properties (e.g., asphalt content) that are known to affect explicit predictors such as AC modulus of elasticity.

The remaining M&C factors in box C are called process control factors (C3) whose specifications enhance the control of other M&C factors. Examples include moisture control during roadbed preparation so that specified levels of soil density and compaction can be attained. Other examples include control of subsurface profiles to enable attainment of specifications for surfacing profile. Some M&C factors may belong in two or more subclasses of box C. Aggregate gradation of an AC mix, for example, may be controlled to enhance both workability of the AC and its ultimate strength.

Secondary relationships (R4) include all equations or algorithms that show interrelations among M&C factors that are represented by box C and boxes B3 and B4. By definition, secondary relationships do not contain indicators for stress/distress/performance, but should account for all M&C factors that are explicit predictors in the primary relationships. As for the derivation of primary relationships, existing data bases for secondary relationships may be either observational or experimental.

As shown in figure 1, both primary relationships (R1 through R3) and secondary relationships (R4) are inputs to the algorithms (R5) that produce performance-related M&C specifications. The specific nature of these algorithms depend upon criteria (box G) that are used to derive performance-related M&C specifications.

As shown in the figure, certain algorithms in R5 are needed for predictions of performance and operational costs associated with pavement deterioration and rehabilitation. Other algorithms are needed for the derivations of acceptance plans and payment schedules that are associated with the M&C specifications. The specifications criteria in box G include, for example, acceptance risks and performance-based economic criteria.

Boxes D through F in figure 1 represent conditions and constraints that must be taken into account by the specifications algorithms. Included are pavement design criteria (box D) that specify particular stress/distress/performance indicators, limiting values for the indicators, and particular primary relationships (R1 through R3) that are to be used as pavement design equations.

It is assumed that the design criteria will also include (1) a design period (e.g., 15 years) during which the selected distress/performance indicators do not reach their limiting values, and (2) associated predictions of expected traffic during the design period, perhaps in terms of ESAL accumulation. A third design criterion is <u>design applications</u> which is either the design period ESAL prediction or some multiple thereof, depending upon the reliability level that has been selected.

Another class of constraints for the specifications algorithms is represented by available M&C resources (box E) and their associated costs (box F). As indicated, the M&C resources will generally represent various options for materials (e.g., aggregate sources) and construction methods (e.g., paving equipment and procedures).

Unit costs in box F must cover not only options for materials and pavement construction, but should also include data for estimating routine maintenance costs and user costs for various levels of pavement condition. If the optimization criteria relate to performance periods beyond the initial period, the cost data must provide inputs for estimation of rehabilitation costs.

The final element of the framework (box H) represents performance-related M&C specifications that are derived via the algorithms in R5. It is assumed that the specifications include target levels (H1) and/or specification limits (H2) for all M&C factors that relate to the pavement's structural design. Specifications for some factors might include target levels and lower limits only (e.g., surface thickness), other specifications might have both upper and lower limits but no target level (e.g., aggregate gradation). Other specifications might have only a lower limit (e.g., AC tensile strength), or an upper limit (e.g., surface profile deviation).

In general, it may be assumed that target levels are based on specific relationships among R1 through R4, subject to criteria, conditions and constraints imposed by items in boxes D through G. It can be expected that levels will be <u>assumed</u> for some factors and that the algorithms will indicate alternative combinations of levels for remaining M&C factors, at least whenever the necessary relationships (R1 through R4) are available.

Levels for some factors will, of course, be specified through State requirements and/or through M&C standards that have been set by the American Association of State Highway and Transportation Officials (AASHTO) or American Society for Testing and Materials (ASTM).

Although some specification limits may also be determined by requirements and standards, the algorithms should make appropriate use of (1) error distributions for the relationships that determine target levels and (2) normal variability in M&C factors. It will be assumed that (2) is an essential aspect of all secondary relationships in R4.

After target levels and/or specification limits are produced by the algorithms, acceptance plans (H3) are developed for those factors whose levels can affect the acceptance or rejection of materials and/or pavement layers. In the simplest case an acceptance plan would define the "lots" to be sampled, time/space sampling points, measurement procedures for the samples, and measurement statistics (e.g., percent within tolerance limits) that will lead either to acceptance or rejection of a given lot. An essential aspect of any acceptance plan is its operating characteristic, i.e., the probability that lots of given quality (with respect to the M&C factor that has been evaluated) will be accepted. It is assumed that the unit costs in box F include M&C inspection and quality control expenditures.

The fourth facet of performance-related specifications includes payment plans (H4) that determine the extent to which the contractor's bid price will be adjusted as a consequence of specific (or multiple) characteristics of the as-built pavement lots. In general, payment plans may be expressed as pay factors (e.g., ranging from 0.5 to 1.2) that correspond to differences between expected performances of the design pavement and the as-constructed pavement.

The foregoing overview of the framework represented by figure 1 implies that the algorithms in R5 are necessarily extensive and complex. Although considerable research effort is required to finalize other framework elements, particularly the secondary relationships (R4), it appears that the algorithm development will be even more demanding. To the fullest possible extent, the eventual algorithms will draw upon and be consistent with counterpart algorithms that have been developed in other related studies.

CHAPTER 3. PRIMARY RELATIONSHIPS

This chapter covers and provides specific examples of the three types of primary relationships that were shown in figure 1, namely:

- R1 - Stress prediction relationships for various indicators of pavement response to single loading applications.
- R2 - Distress prediction relationships for various indicators of pavement distress, including singular distress modes and composite indicators of overall distress.
- R3 - Performance prediction relationships for the time periods and/or traffic accumulations for which pavement distress remains at acceptable levels.

Table 1 is a general classification scheme for the variables that are contained in the primary relationships. The left-hand column lists the indicators whose values are functions of the predictors listed in the right-hand column. Thus, the dependent variable for any particular relationship is in the first column, and the corresponding independent variables are among those listed in the second column.

Stress indicators are dependent variables in R1 relationships but can be predictor variables in R2 relationships (see class 226). Moreover, certain distress indicators can be dependent variables in some of R2, and auxiliary independent variables in other R2 relationships (see class 227).

Each type of relationship is discussed, respectively, in the sections that follow. Within each section, specific primary relationships are identified and the relevant portions of table 1 are expanded to include more specific indicators and predictors. Objectives for each section are to:

1. Identify all predictors that are related to asphalt concrete pavement materials and construction, particularly for the AC surfacing component.
2. Select a small number of relationships that are candidate elements of the algorithms that will be used to derive performance-related M&C specifications.
3. Discuss for each selected relationship, the sensitivity of the predicted variable to changes in predictor variables.
4. Estimate the nature and extent of prediction errors that are not explained by the predictors.

STRESS PREDICTION RELATIONSHIPS

This section describes many of the available analytical (and empirical) response models that can be used to predict stresses, strains and/or deformations in AC pavements. This section is mostly a condensation of reference 14 with some enhancements for the models that were not covered.

Table 1. General classification of variables in primary relationships for flexible pavements.

R1. STRESS PREDICTION RELATIONSHIPS

11. STRESS INDICATORS	12. STRESS PREDICTORS
111. Deflections	121. Loading Factors 122. Moisture/Temperature Conditions
112. Strain Components	123. Surfacing Factors 124. Base/Subbase Factors
113. Stress Components	125. Roadbed Factors

R2. DISTRESS PREDICTION RELATIONSHIPS

21. DISTRESS INDICATORS	22. DISTRESS PREDICTORS
211. Singular Distress Indicators 2111. Cracking 2112. Rutting 2113. Ravelling 2114. Moisture Damage 2115. Skid Resistance 2116. Wear Resistance	221. Traffic Factors & Age 222. Environmental Factors 223. Surfacing Factors 224. Base/Subbase Factors 225. Roadbed Factors
212. Composite Distress Indicators 2121. Roughness 2122. Serviceability Loss 2123. Condition Rating Loss	226. Stress Indicators 227. Auxiliary Distress Indicators

R3. PERFORMANCE PREDICTION RELATIONSHIPS

31. PERFORMANCE INDICATORS	32. PERFORMANCE PREDICTORS
Number of Equivalent Single Axle Load Applications (ESAL) at Acceptable Levels of Distress Indicators	Distress Predictors in Classes 221-227.

For flexible pavements, the models can each basically be classified under one of the following four categories:

- Empirical.
- Multilayered elastic solid.
- Multilayered viscoelastic solid.
- Finite element idealizations.

The first category refers to models that have been derived through mathematical or statistical analysis of field data. The remaining three categories are all mechanistic models that rely on theory and the fundamentals of engineering mechanics in solving for a particular response.

Empirical Models

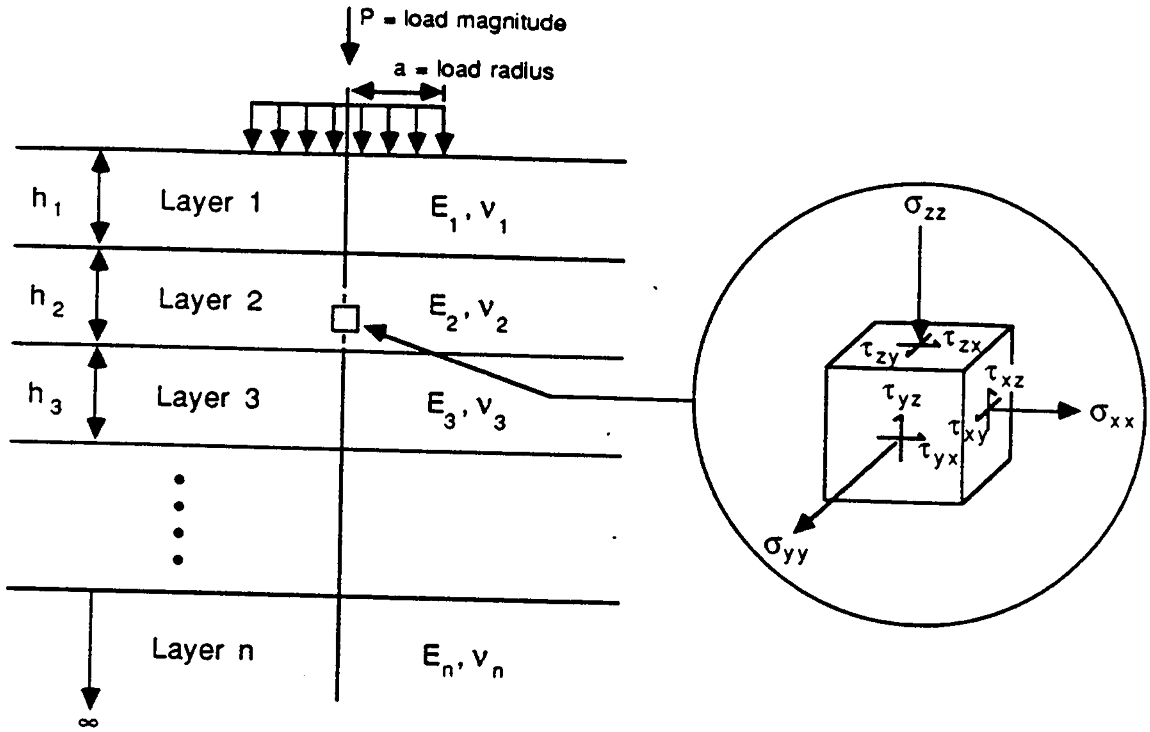
Similar equations were derived for other parameters. These equations are all very useful in evaluating pavement behavior and predicting performance at the AASHO Road Test. However, they lose their applicability once environmental and loading conditions outside those experienced at the Road Test are encountered. This explains why the analytical or mechanistic models described next are so much more attractive than any empirical models. They are capable of predicting pavement behavior and response for a much wider range of conditions.

Multilayered Elastic Analysis Models

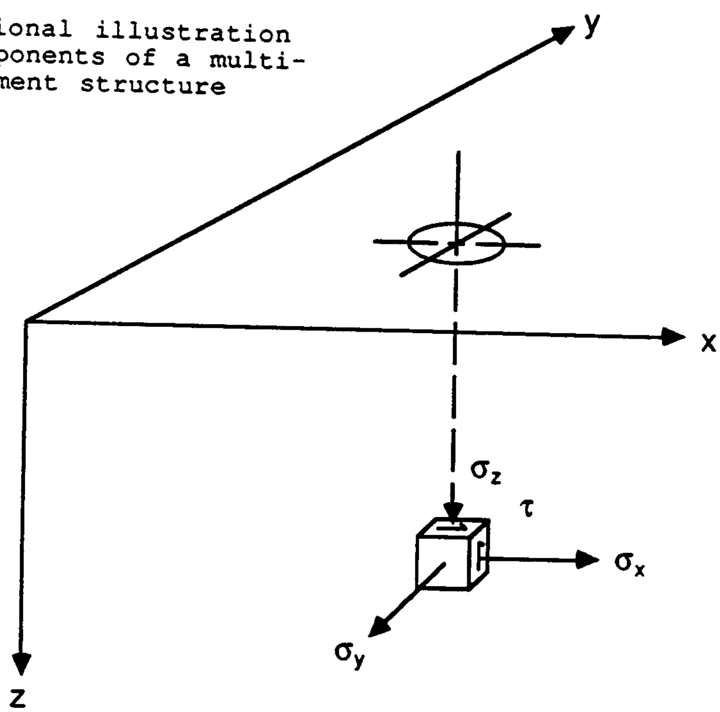
In this analytical methodology, the pavement is modeled as a series or "stack" of individual layers having unique characteristics (see figure 2a). Each layer is assumed to be infinite in all horizontal directions, and the materials that compose the layers are considered to be homogeneous, isotropic and linear elastic in response. (Note: There are some models that incorporate ad-hoc procedures to treat the nonlinear response of materials to stress.) The materials in each layer are characterized by their thickness (h_i), elastic or Young's modulus (E_i), and Poisson's ratio (ν_i). Some methods also consider the unit weight of the layer materials; however, most assume the layers are weightless.

Loads applied to the pavement surface are assumed to have circular contact areas with uniform contact pressures. Most methods can only simulate vertical loading; however, there is at least one that permits tangential surface loads. Many of the available methods also permit the consideration of multiple surface loads (usually up to 10). Most methods also assume that there is full friction (i.e., no slippage) at the interfaces between the layers, although there is at least one method that does permit variable friction at the layer interfaces.[14]

As illustrated by the diagrams in figure 2, a variety of normal and shear stresses can be computed on the faces of a three-dimensional differential element anywhere within the structure. Corresponding strains and displacements due to load can also be determined. Some models even provide for the computation of maximum principal stresses and strains using a Mohr's circle-based procedure. For those that permit the use of multiple loads, the principle of superposition is used to combine the effects at any designated point.



a) Two-dimensional illustration of the components of a multi-layer pavement structure under load.



b) Illustration of coordinate system.

Figure 2. Schematic representation of multilayer elastic pavement structure.

For one-, two- and three-layer structures, hand/graphical solution techniques have been developed through an evolutionary process by a multitude of researchers. These equations and nomographs have been assembled and published in a single textbook.[15] These methods do, however, have some problems (see appendix A).

By far, the quickest and most accurate way to develop solutions is through the use of the computer programs that are currently available. These computer programs make use of integral transform procedures and are based on the solutions originally developed by Burmister:[16]

- BISAR.[17]
- CHEV.[18]
- ELSYM.[19]
- PDMAP.[20]
- VESYS.[21]
- CHEVIT.[22]

Table 2 provides a summary comparison of the capabilities of each of these multilayered elastic analysis programs.

Although these computer programs are relatively fast compared to some of the other more complex methods, there are occasions (particularly on microcomputers) where even faster operational speeds are desirable. This and the need to study the statistical significance of many of the independent variables has led to the development of regression equations that simulate the output of the analytical programs. Appendix A provides some examples of these kinds of approximation functions.

Multilayered elastic solid based modeling procedures have been used for the analysis of both flexible and rigid (PCC) pavements. However, they do have some weaknesses for both pavement types:

- For flexible pavements, there is a limitation when analyzing layered systems consisting of unbound granular layers. Because of their lack of cohesion, these materials have little capability to withstand the levels of tensile stress that might be generated by one of the theoretical elastic layer models. (This problem is less profound in rigid pavements since the PCC slab carries most of the stress.) The likelihood of prediction of this unrealistic condition is greatest when the ratio of elastic moduli between adjacent layers exceeds a practical value (generally between 1.5 and 4.0). To treat this phenomenon, some "ad hoc" procedures have been developed that essentially adjust layer moduli to ensure that significant tensile stresses are not developed in the unbound layers.

Table 2. Comparison of multilayered elastic analysis computer programs.[14]

Program (Ref)	Number of Layers (max.)	Number of Loads (max.)	Continuity Conditions at Interface	Probabilistic Considerations	Program Source	Remarks
BISAR (17)	10	10	Full continuity to no friction	No	Shell International Petroleum Co., Ltd., London, England	1. Relatively long running time since complete set of stresses and strains provided for each point. 2. Considers horizontal as well as vertical loads.
CHEV (18)	5	2	Full continuity	No	Chevron Research Company	1. Nonlinear response of granular materials accounted for in DAMA program of the Asphalt Institute which makes use of CHEV program.
ELSYM (19)	10	100	Full continuity to no friction	No	University of California, Berkeley	1. Short running time for particular point.
PDMAP (20)	5	2	Full continuity	Yes	National Cooperative Highway Research Program (Project 1-10B)	1. Running time is long for degrees of reliability other than 50 percent (the deterministic mode). 2. Iterative process used to arrive at moduli for untreated granular materials.
VESYS (21)	5	2	Full continuity	Yes	FHWA-US DOT	1. Running time is long in probabilistic mode. 2. Program considers materials both as time independent (elastic) and time dependent (viscoelastic).
CHEVIT (22)	5	12	Full continuity	Yes	U.S. Army CE Waterways Experiment Station	1. Modification of CHEV program. 2. Includes provisions for stress. Sensitivity of granular layers.

- For PCC pavements, the procedures are unable to treat the effects of discontinuities that may exist in the structure (i.e., cracks, joints, nonuniform support, etc.). Direct computation of stresses, strains and displacements is only possible for interior load and full support conditions. Edge and corner loads, voids and variable load transfer at joints/ cracks must all be treated by applying an adjustment factor derived by some other analytical means, such as finite element idealizations.

Multilayered Viscoelastic Analysis Models

Pavement representation in this multilayered analysis also follows the schematic representation of figure 2. The only difference, when compared to the elastic case, is that time-and-temperature-dependent material properties are used in lieu of the elastic moduli, E_i. The most well-known of the programs of this type is VESYS; in its most recent form, it can be operated in either the elastic or viscoelastic mode.[21] If used for viscoelastic analysis, a creep compliance, both as a function of time of loading and temperature, must be input for each of the pavement layers.

For asphalt concrete, the creep compliance, defined as:

$$D(t) = \frac{\epsilon(t)}{\sigma_o} \tag{1}$$

where:

$\epsilon(t)$ = time dependent strain
σ_o = applied creep stress

can be used to represent the stiffness characteristics of the layer of interest and seasonal temperature variations can be considered. Compliances for a range of times must be input to the program.

It is noted that, if the VESYS program is run in the viscoelastic mode, the required computer time is seven to eight times that for computations in the elastic mode. It should also be noted that the VESYS program permits estimates of distress as well as determinations of stresses, strains, and deflections. In this sense, then, the program is more versatile than the multilayer elastic analyses described in the previous section. The program permits estimates of fatigue cracking, permanent deformation, and a determination of present serviceability as a function of loading.

Finite Element Idealizations

The development of the finite element method has produced analysis capabilities that far exceed those of the multilayered theory. There are some trade-offs, however, in that increased attention is required in data preparation and output interpretation.

For analysis by this method, the body to be analyzed is divided into a set of elements connected at their joints or nodal points. The cylinder shown in figure 3 is an example. The continuous variation of stresses and strains in the real system is replaced by an assumed linear variation of

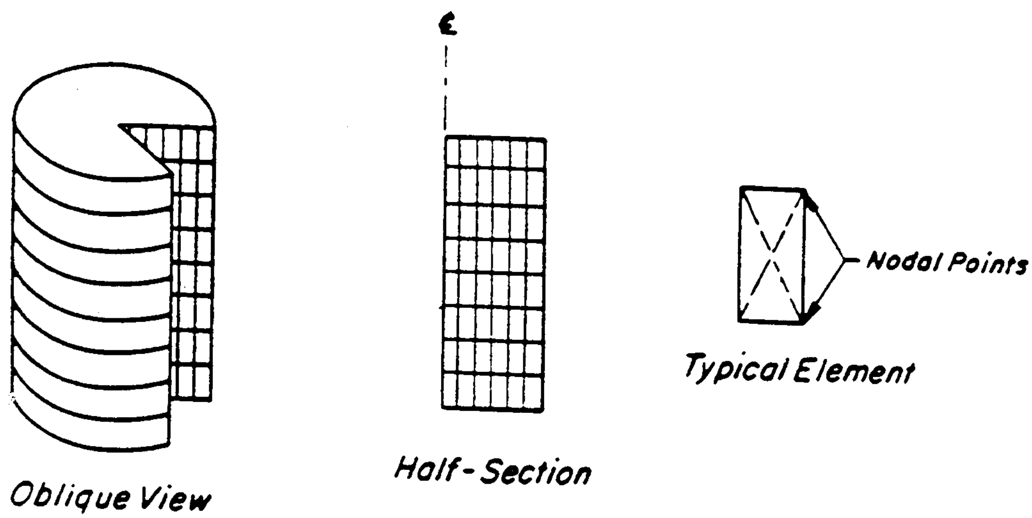


Figure 3. Finite element idealization of a cylinder.

displacements, and hence constant stresses and strains within each element. This assumption satisfies the requirements of compatibility of displacements between elements. For a given element geometry and constitutive equation, the stiffness matrix relating displacements and loads at the corners of each of the basic triangular elements is established. The four triangular elements forming one rectangular element are generally combined, eliminating the common nodal point. Combinations of the element stiffness matrices yield the symmetric banded matrix for the entire structural assembly, which is modified using known displacements at bound axes. Solution of this system of linear equations yields all nodal point displacements, from which the element strains and stresses are computed. The average of the stresses in the four triangular elements gives the best estimate of the stresses at the centroid of the rectangular element.

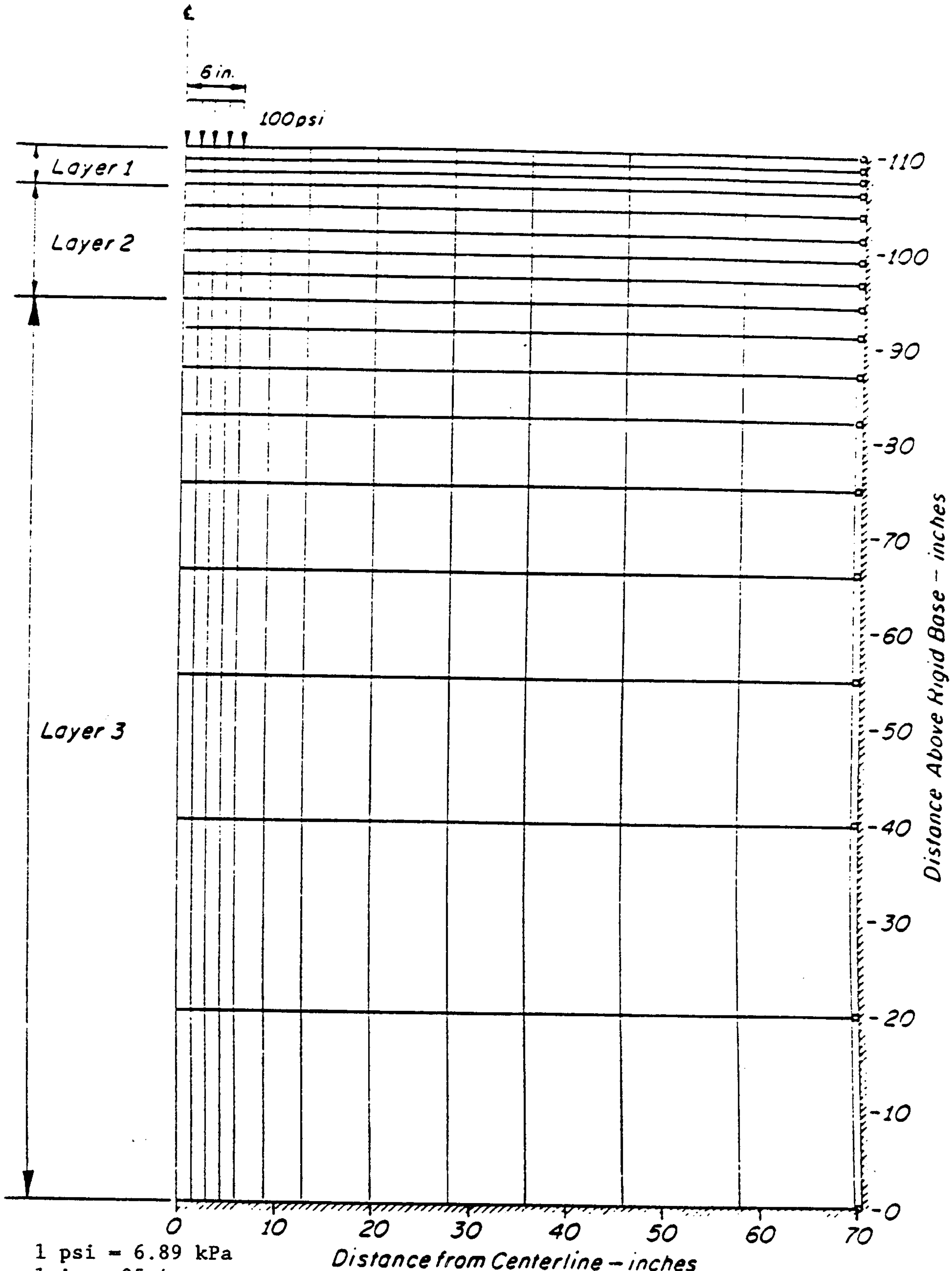
The element configuration must be carefully selected to optimize the results (see figure 4, for example). Generally, the accuracy is improved by the use of a finer mesh, particularly in areas of rapidly varying stresses. However, the greater number of elements increases the computational time and therefore the costs. Dehlen has suggested that an optimum rectangular mesh has finer vertical subdivisions near the surface and in both materials near layer interfaces; and finer radial subdivisions both near the axis of symmetry and near the edge of the loaded area (see figure 4).[23]

This procedure can be used directly for analyzing systems with nonlinear elastic materials. Thus, it is well suited for the study of asphalt surface pavements. Special computational techniques permit consideration of temperature and moisture gradients and voids within the pavement structure. Variable layer properties (thickness and deformation properties) can also be modelled.

Two- and three-dimensional finite element models are available. Ideally, it is desirable to use three-dimensional models to determine the response of the pavement to changes in temperature, moisture, etc. Unfortunately, the cost difference between two- and three-dimensional models can be several orders of magnitude, particularly when very small elements (fine meshes) are being used to increase the observed accuracy of small-scale responses. However, with the advent of increasingly advanced personal and microcomputers these problems are becoming less critical.

Good estimations of stress, strain and deflection can be obtained using the finite element technique provided a sufficiently fine mesh of mostly square elements is used with proper element properties and boundary locations. Finite element techniques offer the most valid approach to modelling the responses of both flexible and rigid pavements to all types of loadings, climatic conditions and support conditions.

A well-known program using a finite element approach is ILLI-PAVE. The structural model represents the pavement as an axisymmetric solid of revolution. Nonlinear properties and failure criteria of the pavement layers are incorporated in the ILLI-PAVE finite element model. Using the results of ILLI-PAVE for full-depth asphalt concrete pavements, simplified analysis algorithms have been developed. Some of these algorithms are as follows:



1 psi = 6.89 kPa
1 in = 25.4 mm

Figure 4. Finite element configurations used for analysis of homogeneous and layered systems.(23)

$$\log \epsilon_{AC} = 5.746 - 1.599 \log T_{AC} - 0.774 \log E_{AC} - 0.097 \log E_{RI} \quad (2)$$

$$N = 5 \times 10^{-6}(1/\epsilon_{AC})^{3.0} \quad (3)$$

where

T_{AC} = asphalt concrete thickness (inches)
E_{AC} = asphalt concrete modulus (ksi)
E_{Ri} = subgrade modulus
ϵ_{AC} = asphalt concrete radial tensile strain (microstrain)
N = number of strain repetitions to failure

DISTRESS PREDICTION RELATIONSHIPS

This section is concerned with relationships (R2 in figure 1) for the prediction of specific distress indicators from predictors that include traffic factors, environmental factors, roadbed soil factors, and structural factors. A high percentage of all existing flexible pavement distress prediction relationships are identified in the 1984 FHWA cost allocation study and/or in the 1986 AASHTO Guide for Design of Pavement Structures as reflected in references 14, 24, and 25. A comprehensive review of performance models for hot-mix asphalt pavements is presented in appendix B of reference 13.

Although additional relationships have been reported elsewhere in the pavement research literature, it is assumed that relationships in the foregoing references will provide a substantial and adequate basis for determining the degree to which various types of flexible pavement distresses depend on factors that are associated with the materials and construction of flexible pavements.

A logical structure for the identification of distress relationships and predictors is given in table 3 which is an extension of the R2 portion of table 1. Distress indicators (class 21) are again listed in two categories, one (class 211) for six types of singular distress and one (class 212) for three types of composite distress. It is acknowledged that several distress types, most notably cracking, could be further classified into still more specific subclasses.

Distress predictors are listed in the right-hand column of table 3 in seven major classes: 221 through 227. The first two classes are for traffic, age, and environmental factors that affect pavement distress, performance, and therefore pavement design, but do not relate specifically to M&C variables. They must, however, be included in the present study so that assessments can be made of the relative effects of traffic, environment, roadbed soil, and structure on any particular type of distress.

Primary structural variables are listed in some detail under surfacing (class 223), base/subbase (class 224), and roadbed (class 225) factors.

The last two predictor classes are for stress indicators (class 226) and auxiliary distress indicators (class 227) that are used as predictor variables in certain distress relationships.

Table 3. Distress prediction variables and selected relationships.

21. DISTRESS INDICATORS	22. DISTRESS PREDICTORS
Dependent Variables	Independent Variables
211. SINGULAR DISTRESS	221. TRAFFIC FACTORS AND AGE
2111. Cracking	2211. Loading Characteristics
2112. Rutting	2212. No. of Loadings
2113. Ravelling	2213. Age
2114. Moisture Damage	222. ENVIRONMENTAL FACTORS
2115. Skid Resistance	2221. Moisture/Precipitation
2116. Wear Resistance	2222. Temperature/Freezing
212. COMPOSITE DISTRESS	2223. Freeze-Thaw
2121. Roughness	223. SURFACING FACTORS
2122. Serviceability Loss	2231. AC Thickness
2123. Condition Rating Loss	2232. AC Strength
	2233. AC Stiffness
	2234. AC Durability
	2235. Density
	2236. Initial Profile
	2237. Initial Skid Resistance
	2238. Segregation
	224. BASE/SUBBASE FACTORS
	2241. Type Material
	2242. Thickness
	2243. Stiffness
	2244. Drainage
	225. ROADBED SOIL FACTORS
	2251. Type/Gradation
	2252. Strength
	2253. Stiffness
	226. STRESS INDICATORS
	2261. Deflections
	2262. Strains
	2263. Stresses
	227. AUXILIARY DISTRESS INDICATORS
	2271. Pumping
	2272. Bleeding

A special type of relationship that is not truly a distress prediction equation in that it does not predict any particular amount of cracking, but rather predicts the number of stress applications at which fatigue cracking will occur, will be discussed in the section that follows.

PERFORMANCE PREDICTION RELATIONSHIPS

For the purposes of this study, pavement performance will be defined as the amount of acceptable service that the pavement provides before major rehabilitation is required.

It is assumed that one or more distress indicators, D, are used as criteria for the level of service that is provided at any point in time, and that for each indicator there is an unacceptable (or terminal) level, D^*, that represents the need for rehabilitation. For simplicity, it is assumed that all distress indicators have zero values at the beginning of any phase of the pavement's life cycle. Thus, level of service is represented symbolically by:

Acceptable Service Levels: $0 \leq D < D^*$

Unacceptable Service Levels: $D \geq D^*$

where it is understood that D represents one or more distress criteria such as cracking, rutting, or serviceability loss.

Amount of acceptable service will be defined as the number of load applications carried by the pavement during the period of acceptable service levels. If the loading characteristics are constant for all applications, the symbol N will be used for the number of constant-stress applications that correspond to any acceptable level of D. The symbol N^* will be used to denote the number of constant-stress applications that have accumulated when D reaches its terminal level, D^*.

If, as in normal highway operations, stress levels (S) vary from vehicle to vehicle and from time to time for any given application, then one stress condition can be defined to be a standard stress level, S_o. The number of loading applications at stress level S_o will be denoted by N_o whenever D is less than D^*. When $D = D^*$, the corresponding number of standard stress applications is $N_o^* (S_o)$.

For any non-standard stress level, S_i, the number of applications at which $D = D^*$ is $N_i^* (S_i)$, and the stress equivalence ratio (SER) between standard and non-standard applications is defined as follows:

$$\text{For } D = D^*, \quad SER_i = N_o^* (S_o) / N_i^* (S_i) \tag{4}$$

If all stress determinants other than axle load (e.g., AC thickness or roadbed soil modulus) are at the same levels for both S_o and S_i, the corresponding SER is a load equivalence ratio (LER) defined as follows:

$$\text{For } D = D^*, \quad LER_i = N_o^* (SAL) / N_i^* (AL_i) \tag{5}$$

where SAL is a standard axle load and AL_i is the axle load for stress level S_i. Conventionally, SAL is taken to be an 18,000-lb (8170-kg) single axle load, but other load factors such as tire pressure and lateral placement must also be specified for the standard loading.

Since highway traffic is comprised of many different axle loadings, when $D = D^*$ the pavement will have received N_i applications of axle load AL_i, for i = 1, 2, ..., but it is not expected that any N_i will have reached N_i^*.

It is conventional to assume that any distress level D that is reached after N_i applications of AL_i would also be reached by some number of standard axle applications that is a multiple of N_i. The multiplier for N_i is called the load equivalence factor for AL_i and is assumed to be the load equivalence ratio given by equation 5. Thus, by definition:

$$LEF_i = N_o^* / N_i^* \tag{6}$$

and is relative to D, D^*, SAL, AL_i, and other stress determinants.

For any particular axle loading (AL_i) and corresponding number of applications (N_i) the equivalent number of standard axle load applications ($ESAL_i$) is defined by:

$$ESAL_i = LEF_i \times N_i = (N_o^* / N_i^*) \times N_i \tag{7}$$

The total number of equivalent applications for N_i applications of AL_i, for i = 1, 2, ..., will be denoted by W and is given by either of the following:

$$W = \sum_i ESAL_i = \sum_i (N_o^*/N_i^*) \times N_i \tag{8}$$

or

$$W/N_o^* = \sum_i (N_i/N_i^*) \tag{9}$$

Terms on the right side of equation 9 are often called load cycle ratios. It can be seen that $W = N_o^*$ when the summation of these ratios is unity. For this reason, the symbol W^* will be used to denote the number of equivalent standard axle load applications at which $D = D^*$.

Equation 9 is one form of Miner's hypothesis where terminal distress (D^*) will be reached when the load cycle ratio summation is unity. Because of the duality of equations 8 and 9, the use of Miner's hypothesis for aggregating mixed stress applications is algebraically identical to the use of load equivalence factors and equivalent load applications for the same purpose. It is therefore easy to show that Miner's original analyses of the fatigue failure of aluminum specimens would have produced the same results had he defined a standard stress level, then calculated equivalent applications for all other stress levels used in the studies.

One obvious flaw in the ESAL summation approach is that the defining relationship (equation 7) holds strictly only for relationships in which D increases linearly with N. For relationships that are quite non-linear, it must be supposed that there can be considerable divergence between W^*

computed from mixed applications and the actual number of standard load applications (N_o^*) that would be observed when $D = D^*$.

Other uncertainties associated with the use of ESAL's stem from the fact that LEF's are generally not the same for different distress indicators (D) and have generally unknown dependencies on the non-load determinants of stress levels. If, as is usually the case, LEF's are derived algebraically from distress prediction equations, then the LEF values can be highly dependent upon the form of the equation, i.e., the mathematical model that is used for D.

In spite of probable shortcomings of LEF's and ESAL's, the accumulated equivalent axle load applications variable, W, and its terminal level, W^*, will be used as primary performance indicators for the derivation of performance-related specifications.

If D represents any distress indicator in table 3, its relationship with distress predictors may be written generally as:

$$D = f\ (2211, W, 2213, 222, 223, 224, 225, 226) \qquad (10)$$

where the predictor variables in function (f) are denoted by their table 3 codes, except for W (code 2212). At the terminal value of $D = D^*$, the corresponding value of W will be denoted by W^*. Thus, for D^* and W^*, equation 10 becomes:

$$D^* = f\ (2211, W^*, 2213, 222, 223, 224, 225, 226) \qquad (11)$$

and may be called an implicit performance prediction equation for W^*. If equation 11 can be solved explicitly for W^*, then:

$$W^* = f'\ (D^*, 2211, 2213, 222, 223, 224, 225, 226) \qquad (12)$$

which is an explicit performance prediction equation, relative to distress indicator D and its terminal value, D^*.

A specific example of equation 12 is the AASHTO Design Guide flexible pavement performance equation that may be written as:[25]

$$W^* = (RHO)[G^{*(1/BETA)}] \qquad (13)$$

where RHO and BETA are functions of distress predictors and (1/BETA) is the exponent for G^*. The variable G is defined by $G = (P_O-P_W)/3$, where P_O is the as-constructed serviceability (PSI) level, and P_W is the pavement's serviceability level after W equivalent standard load applications. Thus, G is a distress indicator for serviceability loss. When P_W reaches a specific terminal level P_W^*, then G^* is the corresponding terminal level for the distress indicator, G. For flexible pavements P_O is generally in the neighborhood of 4.5, and P_W^* is often selected to be 2.5. Thus, for these values of P_O and P_W^*, $G^* = 2/3$ in equation 13.

Nearly all table 3 relationships for distress indicators have been developed in the general form of equation 10 and from statistical analyses of particular data bases. Any of these distress prediction relationships can also be represented in the form of equation 11 or equation 12 and, thus, becomes either an implicit or an explicit prediction equation for the performance indicator W^*. Each such performance prediction equation is, of course, relative to a particular distress indicator, D, and its terminal level, D^*. The mathematical forms (models) for the distress relationship (f) and the performance relationship (f′) have much bearing on the sensitivity of the distress or performance indicators (D or W^*) to changes in the predictor variables.

A special class of performance prediction relationships arises when the distress indicator (D) is defined by only the presence or absence of its terminal level D^*, e.g., the presence or absence of fatigue cracking in a pavement section or laboratory specimen (1 = yes, 0 = no). In these cases there are no antecedent distress prediction relationships (equation 10), and the performance prediction relationships must be developed directly. The general form of these relationships does not include a term (D^*) for the distress indicator and may be written:

$$W^* = f''\ (2211,\ 2213,\ 222,\ 223,\ 224,\ 225,\ 226) \qquad (14)$$

In cases where either equation 12 or equation 14 has been derived to predict "applications to failure" at constant stress levels for all applications, then load equivalence factors (or load cycle ratio summations) must be used to apply the equations to mixed-traffic predictions. An example is represented by the number of loading cycles to fatigue failure in asphalt concrete specimens given by:

$$N^* = A/\sigma^d \qquad d > 0 \qquad (15)$$

where N^* is the number of stress applications to specimen failure through fatigue, and σ is the constant stress level for each application. The graph of equation 15 is thus an S-N curve for asphalt concrete specimens.

If it is desired to use equation 15 to predict fatigue failure after N_1 applications at stress level σ_1, N_2 applications at σ_2, etc., a standard stress level, σ_o, can be defined, and all applications can be converted to equivalent number of stress applications. Thus, for σ_o and for σ_i,

$$N^*_o = A/\sigma_o{}^d \qquad d > o \qquad (16)$$

$$N^*_i = A/\sigma_i{}^d, \text{ for } i = 1, 2, \ldots \quad d > o \qquad (17)$$

The load equivalence factor for converting N_i applications to an equivalent number of N_o application is:

$$LEF_i = N^*_o/N^*_i = (\sigma_i/\sigma_o)^d \qquad (18)$$

Across all stress levels, the accumulated number of equivalent standard stress applications is:

$$W = \sum_i [(LEF_i)\ N_i] = \sum_i [(\sigma_i/\sigma_o)^d\ N_i] \qquad (19)$$

From equation 17, the predicted number of equivalent (standard) applications at failure is:

$$W^* = N^*_o = A/\sigma_o^d \qquad (20)$$

Thus, failure is predicted whenever the right side of equation 19 is equal to the right side of equation 20. As has been stated, this equality condition is algebraically identical to the load cycle ratio condition that:

$$\sum_i (N_i/N_i^*) = 1 \qquad (21)$$

ROLE OF PRIMARY RELATIONSHIPS IN THE DEVELOPMENT OF PERFORMANCE-RELATED M&C SPECIFICATIONS

The main role of primary relationships in the development and application of performance-related specifications is to provide a basis for predicting pavement distress and performance for different pavement structures within a given environment. For a given environment and design levels (target levels) for M&C pavement variables, the primary relationships will predict the extent of pavement distress after the pavement has reached any particular age and has received a particular number of load applications.

If the as-constructed pavement has levels for one or more M&C variables that differ from the corresponding target levels, the primary relationships can predict any differences in distress or performance that arise because the as-constructed M&C variables were not at their specified target levels. Thus, the primary relationships can be used as a basis for construction incentives or penalties that are associated with performance-related M&C specifications.

The second role of primary relationships is to provide a basis for developing secondary relationships that relate M&C variables to one another and to primary relationship predictors that are also M&C variables. The development of secondary relationships is discussed in chapter 4.

A third role for primary relationships is to provide an objective basis for estimating the relative changes in distress and performance that are induced by changes in the primary predictors. These so-called sensitivity analyses can show, for example, the relative effects of load accumulations, environmental factors, roadbed strength, and structural variables. The sensitivity analyses reflect not only the deterministic effects that are provided by prediction equations, but also the prediction errors that are associated with any primary or secondary relationship.

Appendix C of the final report on project 10-26A presents a sensitivity analysis of predicted pavement performance.[13] The following conclusions were reached for the performance model evaluated on that study:

- Stress sensitivity of unbound layers in the pavement is important.
- Pavement service life is sensitive to variations in asphalt concrete thickness, initial PSI, asphalt concrete modulus, surface roughness, and subgrade stress dependency coefficients.
- The effects of base related variables are relatively small compared to the effects of the other design factors.

CHAPTER 4. SECONDARY RELATIONSHIPS AMONG M&C VARIABLES

By definition, a secondary relationship among M&C variables is one that shows how the variables are related to one another and to at least one primary predictor. Also, by definition, any M&C variable that is a primary or secondary predictor is a performance-related variable. It follows that M&C variables that do not appear in established primary or secondary relationships are either not performance-related, or that the defining relationships have not yet been established.

To provide scope commensurate with the project resources, secondary relationships in this study will be restricted to only those M&C variables that are directly related to the surfacing layer of AC pavements. Relative to figure 1, this restriction excludes primary predictors associated with either roadbed soil properties (box B3) or base/subbase properties (box B4). At least for relationships derived from laboratory studies, other excluded M&C variables are those relating to shoulder construction.

As previously discussed, a secondary relationship is one that relates a primary predictor of pavement performance to one or more M&C variables. When combined with primary performance prediction relationships, these secondary relationships provide the necessary link between recognized measures of pavement performance and various M&C factors that have not traditionally been used to predict pavement performance. The literature review for this project uncovered many useful equations that may be classified as secondary relationships. Appendix A provides a list of the selected relationships that are of interest to this study.

This section of the report is provided to assess those available secondary relationships based on their utility in developing a PRS system. Consequently, it is useful at this point to identify the assessment criteria:

- Is the dependent variable in the equation a primary predictor that is commonly found in the available primary relationships? If not, it is not much use in a PRS system. [AC tensile strength, resilient modulus and pavement thickness are the most commonly used primary predictors; however, there are other factors such as fatigue modulus, creep modulus and thermal coefficient that are now finding their way into newer mechanistic models.]

- How many other M&C factors are considered by the relationship in estimating the value of the primary predictor? It is certainly desirable to use an equation that accounts for several key M&C factors that have an effect on the primary predictor, particularly if the factors have interacting effects on the predictor.

- Is the relationship accompanied by pertinent statistical measures (i.e., coefficient of determination, standard error of estimate and number of cases used in derivation)?

A comparison of selected secondary prediction relationships is presented in table 4. The first column provides a cross-reference letter with the secondary relationships listed in appendix A (these relationships

Table 4. List of selected secondary prediction relationships.

Appendix A Cross Reference	Dependent Variable (Primary Predictor in PPR)	Independent Variables that Are also Primary Predictors of Pavement Performance						M & C Variables																	Other Variables		Statistics		
		ATS	DEN	LMS	PAV	TH	VMA	ACP	AGG	APN	ATY	AV	AVC	DV	GTM	LAV	P2	PAW	PVB	RBS	SAG	SB	T	VAG	f	q	R^2	SEE	n
A	SM				X																	X		X					
B	DM											X					X		X				X		X				
C	AE																						X						
D	PFD														X														
E	SM																					X				X			
F	SM						X												X			X							
G	SM							X	X		X												X		X				
H	SM								X				X																
I	MS							X																					
I	HVS							X																					
I	PRD							X																					
J	TDF					X																	X				.797	.048	
K	DM					X																	X				.931	.0728	
L	MR		X							X											X						.659	.680	35
M	DM				X							X				X	X	X					X				.968	.0889	
N	DM				X							X				X	X	X					X				.971	.0849	
O	DM			X										X													.900	.1514	
P	DM	X												X													.744	.2844	
Q	N*																		X	X									

Dependent Variables

AE = Asphalt Concrete Modulus
DM = Dynamic Modulus
HVS = Hveem Stability
MS = Marshall Stability
N = Number of Applications (=1×10^4)
MR = Resilient Modulus
PRD = Percentage of real density
SM = Stiffness of the mix
TDF = Total deflection

Other Primary Predictor Variables

ATS = Asphalt Concrete Tensile Strength
DEN = Density
LMS = Log10 of Marshall Stability (lbs) divided by 100 times Marshall flow (0.01 in.)
PAV = Percent air voids
TH = Thickness
VMA = Volume of mineral aggregate

Materials and Construction Variables

ACP = Asphalt content percentage
AGG = Aggregate gradation
APN = Asphalt penetration
ATY = Asphalt type
AV = Absolute viscocity
AVC = Air void content
DV = Percentage of voids for the modulus specimen minus percent air voids for Marshall Test specimen
GTM = GTM revolutions
LAV = Log10 viscocity of asphalt
PAW = Percentage asphalt by weight
PVB = Percentage volume of binder
P2 = Percentage aggregate passing #200
RBS = Ring and ball softening point
SAG = Percentage of sand in aggregate
SB = Stiffness modulus of bitumen
T = Temperature
VAG = Volume concentrations of aggregates

Other Variables

f = Frequency
q = Mix stiffness/bitumen stiffness

Statistics Variables

R^2 = Coefficient of determination
SEE = Standard error of estimate
n = Number of cases (samples)

were taken from references 26 through 31). The second column lists the dependent variable, normally a primary predictor. The independent variables are listed in three columns: (1) independent variables that are also primary predictors of pavement performance; (2) M&C variables; and (3) other variables. The last column of the table lists the statistics of the equations when available.

Most of the secondary relationships found in the literature are for either the stiffness of the mix (equations A, E, F, G, and H) or the dynamic modulus (equations B, K, M, N, O, and P). In the category of independent variables that are also primary predictors, the percent air voids is the most commonly used variable (equations B, M, and N); under M&C variables, stiffness of the binder (equations A, E, and F), percent aggregate pMwsing #200 (equations B, M, and N), asphalt viscosity (equations B, M, and N), temperature (equations B, C, G, J, K, M, and N), and asphalt content percentage (equations G and I) are the most commonly used.

In general, the following observations can be made that essentially assess the usefulness of the secondary relationships studied:

- No one relationship considered all the potential independent variables. Even if a given factor is considered to be insignificant, it is desirable to have the experimental results to support it.

- Almost half the equations included terms that consisted of other primary predictors. This causes problems in a PRS system in that, although these other primary predictors are significant, they are not directly controllable M&C factors.

- About a third of the equations had important statistics (i.e., coefficient of determination and standard error of estimate) attached to them. In order to consider the variability effects of the individual factors within the system, it is important to have these kinds of statistics.

The assessment of the secondary prediction relationships (in terms of their usefulness in developing a PRS system) indicates the strong need for a statistically designed laboratory experiment to study the effects of the directly controllable M&C factors on selected primary predictors of pavement performance. This assessment was used as a basis for designing the initial laboratory study discussed in chapter 5. It is also used as a basis for designing the future, much larger laboratory study, discussed in the same chapter, and a field experiment.

CHAPTER 5. LABORATORY TEST PROGRAM FOR DEVELOPMENT OF SECONDARY RELATIONSHIPS

The focus of the laboratory study will be on the development and/or verification of secondary prediction relationships (SPR's), which are equations that establish the relationship between M&C variables (such as asphalt content, penetration grade, and aggregate type) and fundamental response variables (which are also known as explicit predictors of pavement performance and include such factors as asphalt concrete resilient modulus, creep modulus and low temperature fracture strength). Primary prediction relationships (PPR's), which establish a connection between various pavement response variables and various pavement performance indicators (e.g., fatigue life, fatigue cracking, low temperature cracking, rutting, serviceability, ravelling, and skid resistance), will only be considered in this study as they relate to SPR's. Together, within the PRS framework, these relationships will permit highway engineers to examine the impacts that many M&C factors have on pavement performance as well as the overall construction specification process.

Figure 5 provides an illustration of the connection between the variables associated with the development of an asphalt concrete pavement PRS system. Pool A identifies many (but not all) of the M&C factors that are amenable to control during the design and construction process. Pool B lists many of the pavement response variables that are known to have some effect on pavement performance in one form or another. These are all highly dependent on one or more of the pool A variables; hence they are not amenable to direct M&C control. These variables are, however, known to have an explicit effect on asphalt concrete pavement performance and have, therefore, been correlated to performance measures much more so than any of the pool A variables. The variables in pool C are those that are actually indicative of the performance of a given pavement. Because of the various distress modes and methods for assessing pavement performance, these variables cover a wide range of conditions.

With an understanding now of the variables in the different pools, it should be clear that secondary prediction relationships (SPR's) connect pool A variables to those in pool B while primary prediction relationships (PPR's) connect pool B variables to those in pool C. It should also be recognized that not all the variables in pool A have an effect on those in pool B and, similarly, not all those in pool B have an effect on those in pool C.

In accordance with figure 5, it should be clear that the objective of this component of the laboratory study is the development of relationships between pool A variables and pool B variables. To accomplish this objective, it was important to maximize the effectiveness of the available funds in both the initial laboratory study and the planned future field study. A statistically-based experiment design approach was required to maximize the number of pool A and pool B variables that could be considered.

LABORATORY STUDY EXPERIMENT DESIGN, VARIABLES AND TEST PROCEDURES

A partial factorial experiment was designed for the laboratory study. Experimental variables were selected from experience in the NCHRP 10-26A and

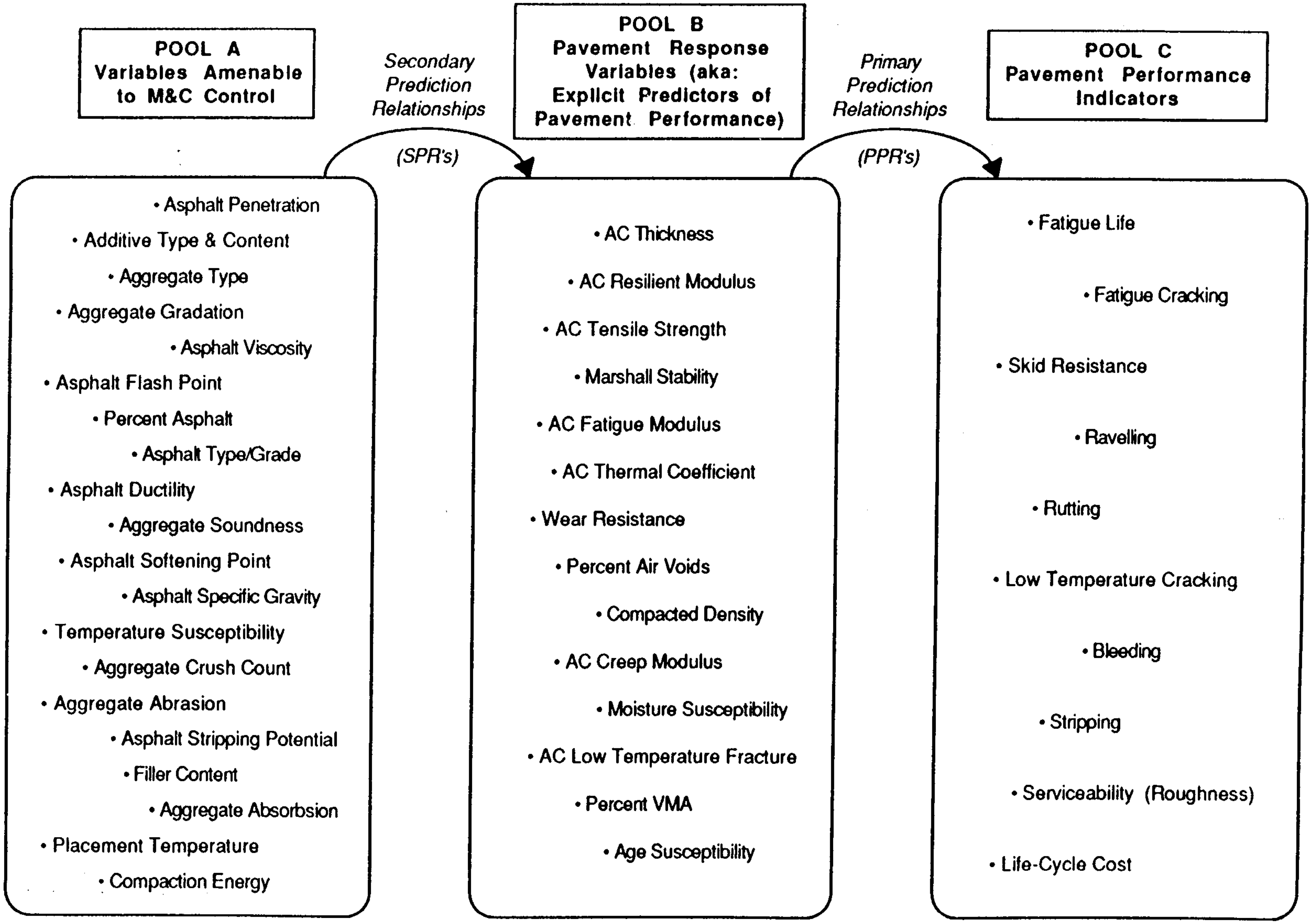


Figure 5. Connection between variables associated with an AC pavement performance-related specification system.

related projects, from the experience of the project research team, and with help from an advisory panel consisting of experienced materials research engineers. Budgetary restraints, and a desire to include factors at three levels, if possible, were major obstacles to overcome in developing an acceptable design. The final experiment design was a 1/6 fractional factorial. This design provided for the testing of 108 out of 648 possible combinations of variables and variable levels contained in a full factorial design. This was an efficient design which permitted the inclusion of many experimental variables at three levels. It was selected because it allowed the estimation of all 7 linear main effects, all 4 quadratic main effects of the factors with three levels, and all 21 linear*linear two-factor interactions. Thus, the grand total of effects accounted for by this experiment was 32. The assumption made to generate this experiment design was that all third order effects were negligible. Table 5 shows the experimental variables and factor levels included in the experiment. All possible cells and the 108 selected for testing are shown in figure 6. The 108 cells were generated using the Algorithm for Computation of Expermiental Designs (ACED) software package. This computer program minimized the average variance of the response estimators over the design region (i.e., the 648 cells), and made the correlation between all possible pairs of effects and interactions (32 total for this experiment) to be as small as possible. All cells were tested in random order.

Experimental Variables

Two asphalts were included: an asphalt with a high temperature susceptibility from a California Valley crude source, and a low temperature susceptibility asphalt from a Boscan crude source. Physical characteristics of these two asphalts are given in appendix B, table 22.

Two aggregates were also selected for the experiment: a non-stripping crushed granite from Watsonville, California, and a stripping granite from Grayson, Georgia. Physical properties of these two aggregates are given in appendix B, table 23.

All of the asphalts and aggregates for the study were obtained from the same sources that provided these materials to the Strategic Highway Research Program, Materials Reference Library (MRL).

Asphalt content was varied at three levels, defined as deviations of 0.75, 0.0 and -0.75 from optimum. Optimum asphalt content was obtained for each aggregate and each gradation of aggregate by compacting samples using the standard Hveem mix design procedure and the AC-20 asphalt. Check tests were made with the AR-4000 asphalt. Asphalt contents at 4 percent air voids were designated optimum.

Compaction was varied at three levels: high, medium and low. Compaction levels were selected to produce a range in air void content, and were maintained constant for all samples compacted at each level in the experiment. This produced, within each compaction level, a range in percent air voids and voids in the mineral aggregate (VMA) that varied with aggregate gradation and asphalt content. Percent air voids and VMA were, therefore, uncontrolled variables in the experiment.

Table 5. Recommended independent M&C variables for laboratory study - plan one.

Variable	No. of Levels
1. Aggregate Stripping Potential (TSR)	2
2. Asphalt Temperature Susceptibility (PVN)	2
3. Asphalt Content	3
4. Anti-Strip Additive (Lime)	2
5. Compaction (To vary voids, etc.)	3
6. Gradation (Sieve #30)	3
7. Filler Content (Sieve #200)	3
	$2^3 \times 3^4$
Total number of cells	648
ACED Fractional Factorial	108

sieve #30 = 600 μm
sieve #200 = 75 μm

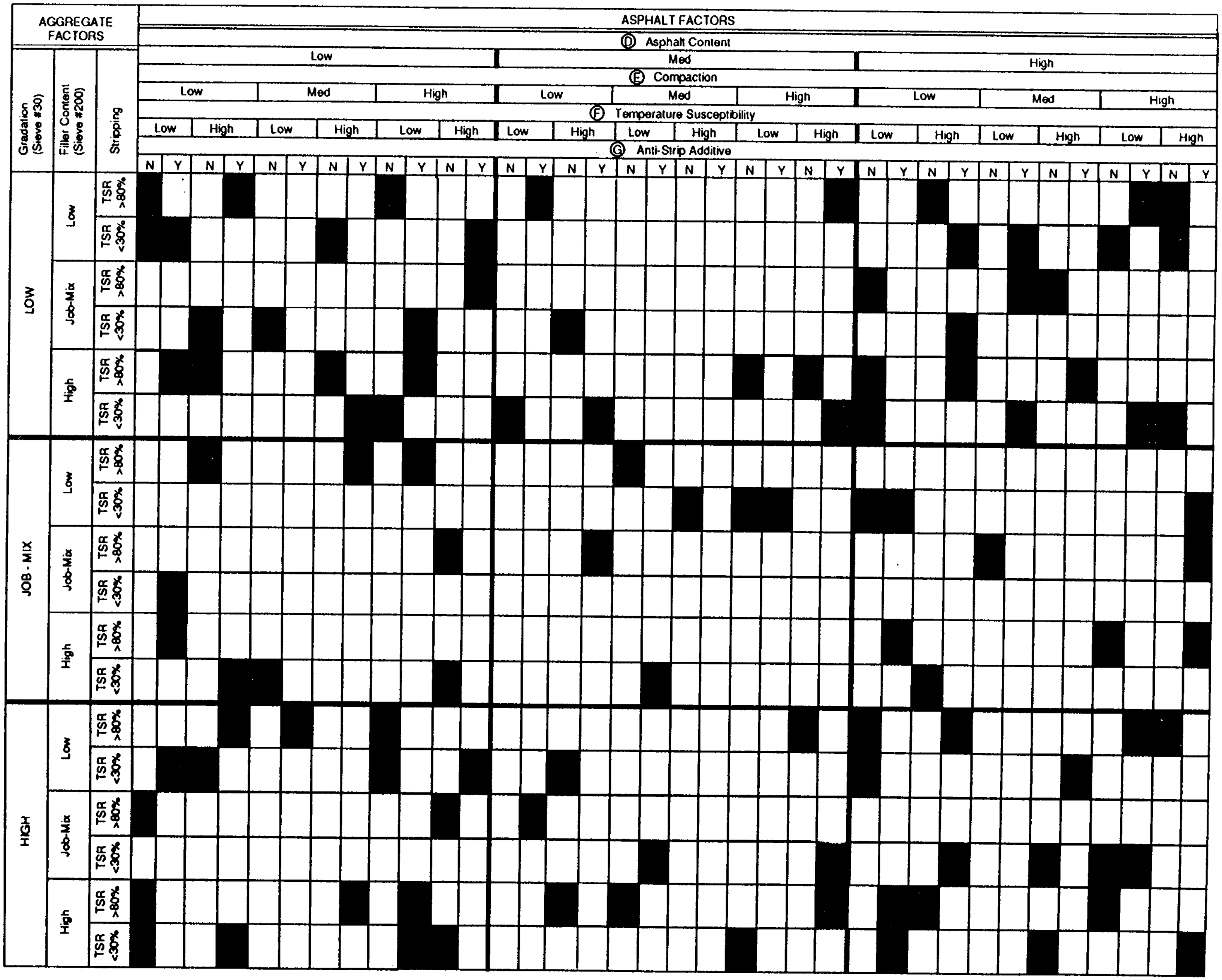


Figure 6. Elements of laboratory experiment.

Three basic gradations were used in the experiment. The percent passing the No. 30 (600 μm) and the percent passing the No. 200 (75 μm) sieves were each varied at three levels with each gradation to produce nine different combinations. Gradation plots are shown in figures 7 through 9. Target levels for the No. 30 (600 μm) sieve were 12, 17 and 30 percent passing. Target levels for the No. 200 (75 μm) sieve were 0, 6 and 12 percent passing. These target levels are shown in table 6. Actual levels ranged from approximately 2 percent minimum to slightly over 12 percent maximum. Actual gradations for the two aggregates are given in appendix B, tables 25 and 26.

<u>Mixing, Compaction and Testing Procedures</u>

Compaction and testing procedures performed on the compacted mixtures are listed in table 7. Tests included in the program were resilient modulus at 77 °F (25 °C), indirect (diametral) tensile strength at 0 °F (-18 °C) and 77 °F (25 °C), diametral fatigue at 77 °F (25 °C), and diametral creep at 104 °F (40 °C).

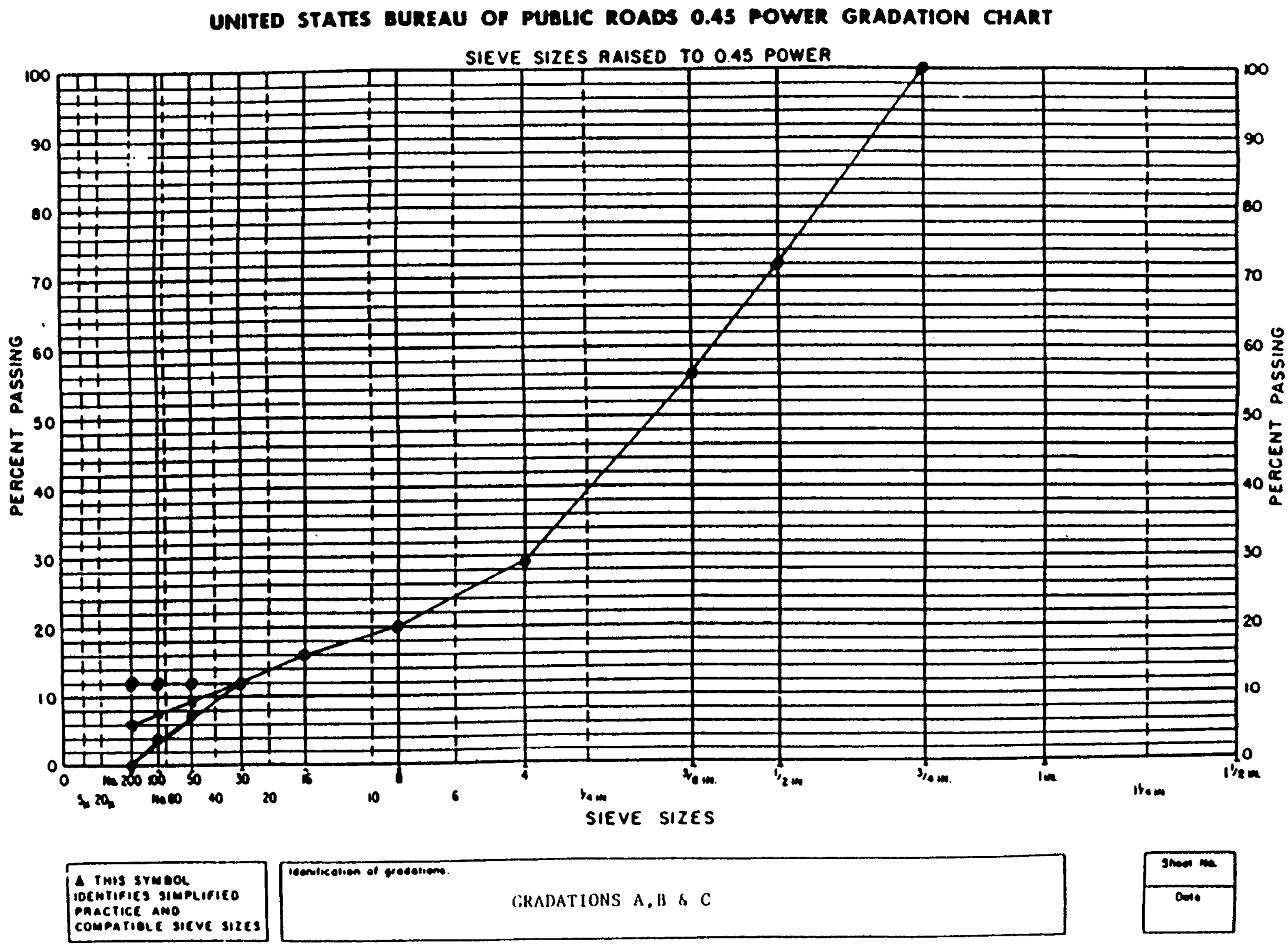
Specimens also were subjected to aging and moisture conditioning. The number of actual tests performed for each test and conditioning, not counting repeat tests to check suspect test results, are given in table 9.

Specimens were prepared and tested, where applicable, in accordance with ASTM methods D1560 and D1561, except that samples were extruded after the leveling load had been applied and that samples had cooled to 77 °F (25 °C) before any conditioning was applied or testing done. Compaction effort with the kneading compactor was adjusted to produce three levels of compaction. Target air voids ranges were 1 to 5 percent for the high compaction level, 5 to 8 percent for the medium level and 8 to 12 percent for the low level (see table 8). The compactive effort was determined on mix design samples for all gradations (A through I). All asphalt contents and gradations included in the fatorial experiment were subjected to the three compaction levels determined using the mix design samples.

Except for the creep tests, cylindrical specimens 2.5 in (64 mm) high and 4.0 in (102 mm) in diameter were tested using the diametral apparatus described in ASTM Method D4123. Creep tests were performed on specimens 4.0 in (102 mm) in diameter and 8.0 in (203 mm) high.

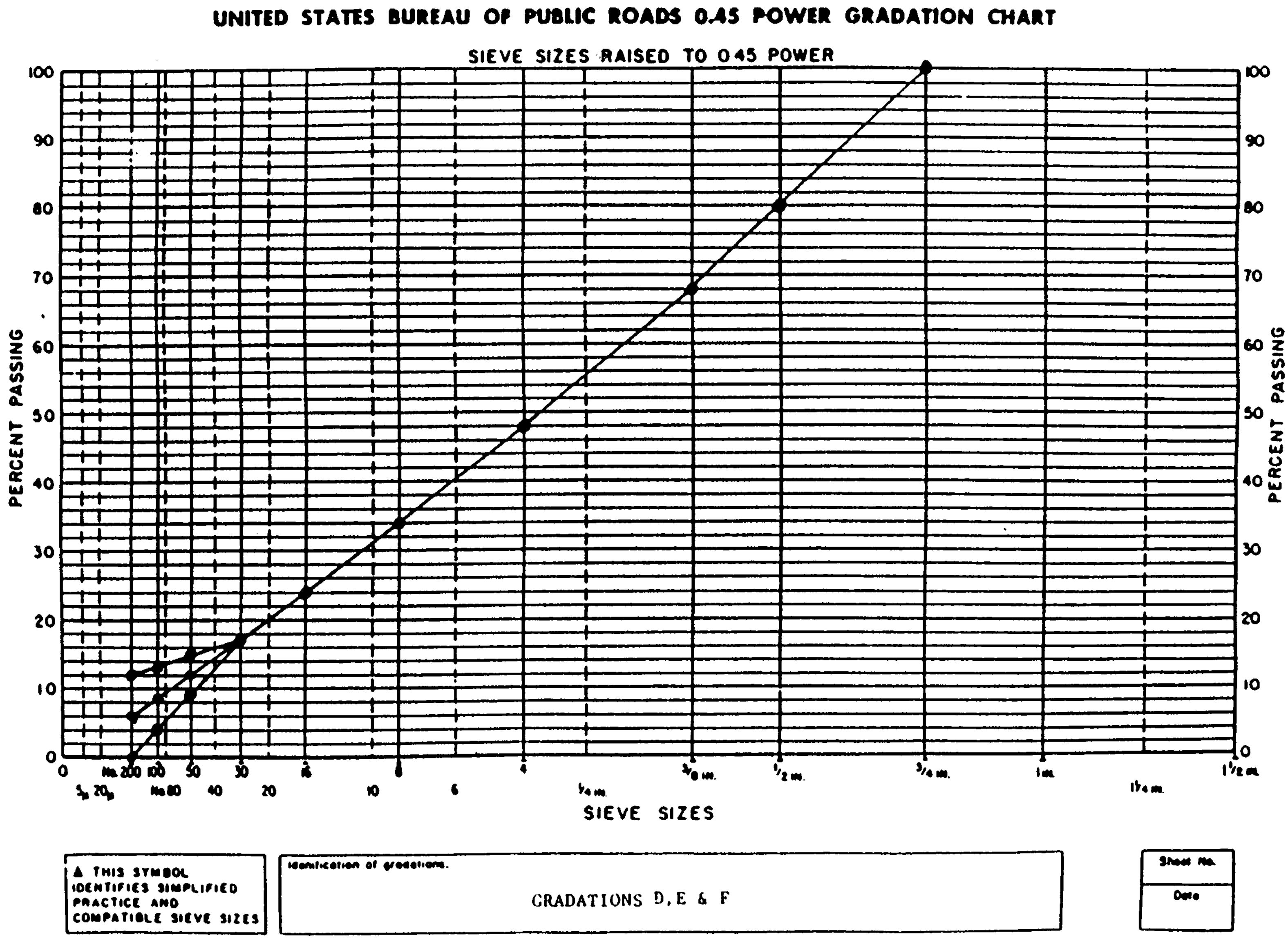
The sample height, resilient modulus, and bulk specific gravity were determined at 77 °F (25 °C) before subjecting the samples to oven-curing at 140 °F (60 °C) for the indicated number of days. Tensile strength measurements were taken after the samples were removed from the oven and cooled to 77 °F (25 °C).

Moisture conditioned samples were treated using a modified Lottman accelerated conditioning procedure. The individual specimens were subjected to a vacuum at 24 in (610 mm) of mercury for 10 minutes, wrapped in plastic film, placed in a sealed plastic bag with 10 ml of water, and cooled to 0 °F (-18 °C) for a minimum of 15 hours. After this time, the samples were unwrapped and placed in a water bath at 140 °F (60 °C) for 24 (±1) hours, moved to a 77 °F (25 °C) water bath for 2 hours, and tested wet for resilient modulus and tensile strength.



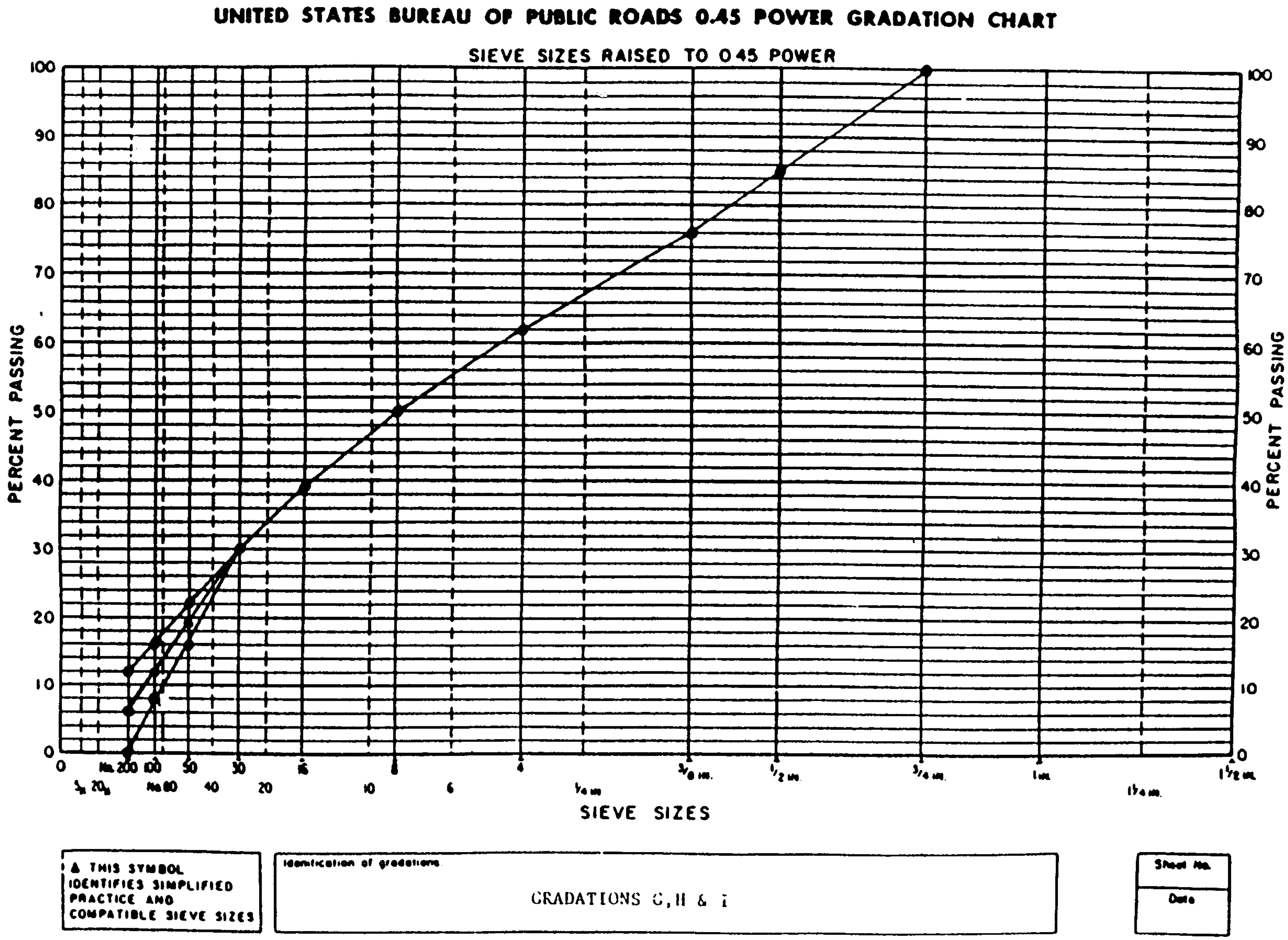
1 in = 25.4 mm

Figure 7. Gradations a, b & c.



1 in = 25.4 mm

Figure 8. Gradations d, e & f.



1 in = 25.4 mm

Figure 9. Gradations g, h & i.

Table 6. Aggregate gradation levels.

Sieve No.	Percent Passing Aggregate Gradation A	B	C	D	E	F	G	H	I
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	72.0	72.0	72.0	80.0	80.0	80.0	85.0	85.0	85.0
3/8 in.	56.0	56.0	56.0	68.0	68.0	68.0	76.0	76.0	76.0
No. 4	29.0	29.0	29.0	48.0	48.0	48.0	62.0	62.0	62.0
No. 8	20.0	20.0	20.0	34.0	34.0	34.0	50.0	50.0	50.0
No. 16	16.0	16.0	16.0	24.0	24.0	24.0	39.0	39.0	39.0
No. 30	12.0	12.0	12.0	17.0	17.0	17.0	30.0	30.0	30.0
No. 50	7.0	9.5	12.0	9.0	12.0	15.0	16.0	19.0	22.0
No. 100	4.0	8.0	12.0	4.0	8.5	13.0	7.5	12.0	16.0
No. 200	0.0	6.0	12.0	0.0	6.0	12.0	0.0	6.0	12.0

1 in = 25.4 mm

Table 7. Compaction and test procedures for laboratory study.

Test Property	Test Method	Level Low	Level Medium	Level High
Compaction procedure[1] -				
Kneading - Primary compaction procedure for test specimens				
Gyratory - Mix design check test only				
Asphalt aging -			see Appendix C	
Moisture conditioning -	Modified Lottman		see Appendix C	
Resilient modulus test -	ASTM D 4123			
Load rate - sec on/off		0.1/2.9		0.1/2.9
Temperature - °F		77		104
Indirect tensile strength test				
Load rate - in/min		0.05		2.0
Temperature - °F		0		77
Diametral fatigue test -	controlled stress			
Load rate -			1 Hz	
Temperature - °F			77	
Diametral creep test				
Load rate - min on/off			60/60	
Temperature - °F			104	

°C = 5(°F-32)/9
1 in = 25.4 mm

(1) Compaction levels are given in table 8.

Table 8. Compaction levels and corresponding air voids ranges.

COMPACTION LEVEL	TARGET AIR VOIDS RANGES (%)
HIGH	1 - 5
MEDIUM	5 - 8
LOW	8 - 12

Table 9. Distribution of number of samples for the factorial design.

Total factorial:	$2^3 x 3^4$ = 648 cells
Special Factorial(1)	108 cells
Total Number of Samples:	1068

Test	Number of Samples from: ACED Factorial (108 Cells)	Replicates (12 Cells)			Total Number of Samples
Resilient Modulus					
(77 °F [25 °C] and 104 °F [40°C])					
Unconditioned	108			12	120
Aging conditioning	108			12	120
Moisture conditioning	108			12	120
Indirect Tensile Strength					
(0 °F [-18 °C] and 77 °F [25 °C])					
Unconditioned	108			12	120
Aging conditioning	108			12	120
Moisture conditioning	108			12	120
Diametral Fatigue(2)					
(Controlled stress, 77 °F [25 °C])					
Unconditioned		24	24	24	72
Aging conditioning		24	24	24	72
Moisture conditioning		24	24	24	72
Diametral Creep(3)					
Unconditioned			12	12	24
Aging conditioning			12	12	24
Moisture conditioning			12	12	24
	Samples for mix designs				60
	TOTAL SAMPLES:				1068

(1) The factorial was obtained using the Algorithm for Computation of Experimental Designs (ACED).
(2) Only replicates were used (2 samples each cell and replicated 2 times).
(3) Only replicates were used (1 sample each cell and replicated once).

Fatigue samples were subjected to a 12-psi (83-kPa) and 30-psi (207-kPa) haversine loading at 10 Hz. A permanent deformation of 0.5 in (12.7 mm) was defined as the failure point.

Creep test specimens were subjected to an axial conditioning using a sine wave loading from 0 to 20 psi (0 to 138 kPa) for 1 minute followed by a 10 second rest period. After conditioning, the specimen was subjected to a static load of 20 psi (138 kPa) for 1 hour. The load was then removed for 1 hour before the total deformation or strain was measured.

CHAPTER 6. DEVELOPMENT OF SECONDARY RELATIONSHIPS

INTRODUCTION

Secondary relationships in this study are defined as those relationships that may be used to predict performance-related properties of AC mixtures from properties of materials that are under the control of the specification writer or contractor. Performance-related properties of asphalt mixtures include resilient modulus, tensile strength, fatigue life and creep resistance. Pertinent material properties include type and grade of asphalt, type and gradation of the aggregate, and such mixture properties as asphalt content, percent air voids, voids in the mineral aggregate, and similar properties. These properties are affected by the mix design process and by control exercised during construction.

One of the objectives of this project was to determine relationships between material properties and performance-related mixture properties using laboratory data generated in the study. The laboratory program, test data and results of a statistical study of the data are presented elsewhere in this report. The purpose of this chapter is to present equations that can be used to predict performance-related mixture properties from routine materials and construction properties determined on material samples or cores obtained at the job site. The relationships can be used, with other relationships called primary relationships, to predict effects of deviations from specifications on pavement performance, establish penalties for nonconformance to specifications, and revise specifications to improve performance.

Mix designs ahead of construction in a central laboratory frequently do not apply to the materials actually used on the job. Aggregate gradations may change, asphalts may be different, and other variations may occur in the mixing process during construction. Placing and compacting may produce mixes that differ substantially from those originally designed. Relationships given in this report are designed to permit the engineer to estimate the effect of these changes using data for the actual materials and mixtures produced at the job site. Changes may be made on-site in materials or construction practices to correct deficiencies. The equations are designed to be used with a hand calculator, and may be reduced to graphs for specific situations, but can be used more effectively with a spreadsheet or computer program on an on-site computer. Several alternative solutions to predict problems can easily be explored in this way.

Where possible only properties (variables) that could be qualified by routine test values were included in the predicition equations. Effective use of the equations will require that testing be done carefully and consistently.

SIGNIFICANT MATERIAL PROPERTIES

Table 10 lists material and mix design properties obtained in the laboratory program that were found to have a significant effect on resilient modulus, tensile strength and other important mixture properties. Considerable engineering judgement was used in selecting the

Table 10. Significant M&C variables.

Dependent Variable	Independent Variables
Resilient Modulus (MR)	Compaction, percent passing sieve #30 percent, asphalt content, asphalt type, percent passing sieve #200
Tensile Strength (TS)	Compaction, percent passing sieve #30, asphalt content, asphalt type, percent passing sieve #200
MR (32 days)/MR (1 day)	VMA, compaction
TS (32 days)/TS (1 day)	Compaction, percent asphalt content
Index of Retained Modulus (IRM)	Additive, percent asphalt content, percent passing sieve #30, percent passing sieve #200
Index of Retained Strength (IRS)	Additive, percent passing sieve #30

sieve #30 = 600 μm
sieve #200 = 75 μm

appropriate variables. Not all variables were found to be significant with a high degree of correlation in the statistical analysis of the data, but they were considered to be important from engineering considerations.

Compaction was found to be an important variable in the analysis of the laboratory data. Unfortunately, compaction level is not an M&C variable that can be defined by a test procedure in the field. It was originally thought that air voids in the compacted mix would serve as a substitute for compaction level in the analysis and resulting equations. However, the effects of compaction on test data actually turned out to be much more complex. For this reason, compaction level appears as an M&C variable in most of the relationships. However, since compaction is not a property that can be determined by direct testing, a procedure was developed to permit the user to estimate a "compaction index" from data that can be determined by routine testing.

Another problem arises from the inclusion of asphalt type, aggregate type, and the use of lime to minimize stripping as M&C variables. Except for asphalt type, these variables were not described in this experiment by properties that could be quantified. Asphalt type is defined both by type and by penetration at 77 °F (25 °C) on the original asphalt.

Statistical Analysis of Laboratory Data

Appendix C contains all of the data used to develop the prediction equations presented in this chapter. Appendix D describes the statistical analysis that formed the basis for selecting prediction variables included in the equations. The SPSS/PC+ (TM) V3.1 statistics software was used to analyze the laboratory test data. The initial analysis used a stepwise multiple regression procedure to find significant variables and two-factor interactions between variables. Results of the initial analyses produced a list of candidate variables that were considered for inclusion in the final relationships. Table 10 shows variables that were indicated, by simple correlations between main variables and two-value products, to be potential candidates for inclusion in the final relationships. Results of the analyses are included in appendix D.

Variability in Test Data

Examination of the results of the statistical analyses, and of the raw data given in appendix C, indicates that not all data scatter is explained by the factors included in the regression models. In some cases the models explain less than 60 percent of the observed variation in the dependent variable. Some of the unexplained variability is quite large, which may indicate that the models could have been improved. An effort was made in selecting factors to keep the models simple, and to include only variables that can be quantified. Also, linear regression techniques were used to develop the models, and it is possible that nonlinear regression techniques would have stronger relationships. However, there is no strong evidence that nonlinear models would have produced substantially better equations.

It appears, from an examination of the data, that much of the data scatter can be attributed to "testing error." Some of the data scatter is related to operator experience level, operator learning requirements, and the use of different operators to perform some of the tests at different times. This is indicated by a fairly strong correlation between the testing time sequence and the magnitude of the difference between estimated and observed test values, or residuals found by regression analysis.

All test results were inspected by the research engineer in charge of the testing laboratory for obvious errors in testing, conditioning or in recording test values. In many cases new samples were prepared and tested. Further checks were made during the analysis of the data, and data points identified as statistical outliers were not used to develop equations.

Another factor of some consequence was that the experiment design included levels of experiment design factors that are possible but which are not always permitted by many specifications. Some combinations of low compaction, high air voids, low amounts of filler and low asphalt content were difficult to handle when heated to 140 °F and could not be tested after aging and moisture conditioning. In addition, aged and moisture-conditioned resilient modulus and tensile strength samples displayed greater unexplained variability in the analysis than unaged or unconditioned samples. In spite of the shortcomings already mentioned, the data are reliable and typical of data generated routinely in many laboratories.

EFFECT OF M&C VARIABLES ON MIXTURE PROPERTIES

Results of the statistical analyses, the decision to use M&C variables that can be quantified, and results of the literature survey described in chapter 4 were used to select a set of M&C variables for the final set of equations for predicting performance-related mixture properties. As indicated above, engineering judgement was relied upon extensively in selecting the final set of variables.

One of the problems discussed above was that compaction level had such a strong influence on the test results that it was left in many of the final equations. Asphalt type also was left in, but not aggregate type. It was found in this experiment that aggregate type was not statistically significant. The equations apply to both aggregates used in this experiment. The use of lime as an antistripping agent was included only in the equations for moisture conditioned properties.

As indicated earlier, compaction level was replaced with a "compaction index" (CI) for use with the prediction equations. Compaction levels were established after the initial mix design tests were run. High compaction was defined as the compactive effort used to perform the mix design tests. Optimum asphalt content was selected at 4 percent air voids. Actual air void contents for high compaction ranged from 0.2 to 17.5 percent for the different conditions of tests. The medium level of compaction was selected to produce an air voids content of approximately 8 percent for the mix design asphalt content. The actual values ranged from 2.8 to 12.6 percent for the different conditions of tests. Similarly, the low level of compaction had a target air voids content of 12 percent, and actual values ranged from 3.0 to 18.5 percent.

A very useful tool in comparing the distribution of values in several groups is the box plot. A box plot is not a plot of actual values. Instead, it displays summary statistics for the distribution. It shows the median, the 25th percentile, the 75th percentile, and values that are far removed from the rest. Fifty percent of the cases have values within the box.

The upper boundary of the box represents the 75th percentile and the lower boundary the 25th percentile. Also shown as horizontal segments are the largest and smallest observed values that are not outliers. These line segments are joined to the boxes through vertical lines. Outliers are shown with the "O" symbol and extreme values with the "E" symbol.

Summary box plots of air voids, VMA, unconditioned resilient modulus, and indirect tensile strength values are shown in figures 10, 11, 12, and 13, respectively.

The length of the boxes in figure 10 is bigger for low and medium compaction. This indicates that the distributions of air voids for those two levels have more variability than the high compaction level. The median value for the low and high compaction levels are closer to the lower boundary of the box, meaning that these two levels of compaction have positively skewed data. The box plot for the high compaction level also shows an outlier (random cell number 5) and an extreme value (random cell number 13).

The box plots for both unconditioned resilient modulus and tensile strength (figures 12 and 13) show a greater variability in the data for asphalt type B than for asphalt type A.

PREDICTION EQUATIONS

Equations for predicting significant performance-related mixture properties developed from statistical analysis of the laboratory data using the SPSS/PC statistical analysis program are presented below, and listed in table 11. The equations satisfy the assessment criteria outline in chapter 4 (i.e., commonly found primary predictors, use of several M&C variables, and pertinent statistical measures).

The notation used in these equations is as follows:

CI	=	compaction index
MR	=	resilient modulus at 77 °F (25 °C)
TS	=	tensile strength at 77 °F (25 °C)
IRM	=	index of retained modulus
IRS	=	index of retained strength
VMA	=	voids in mineral aggregate (percent)
%VOIDS	=	percent air voids (percent)

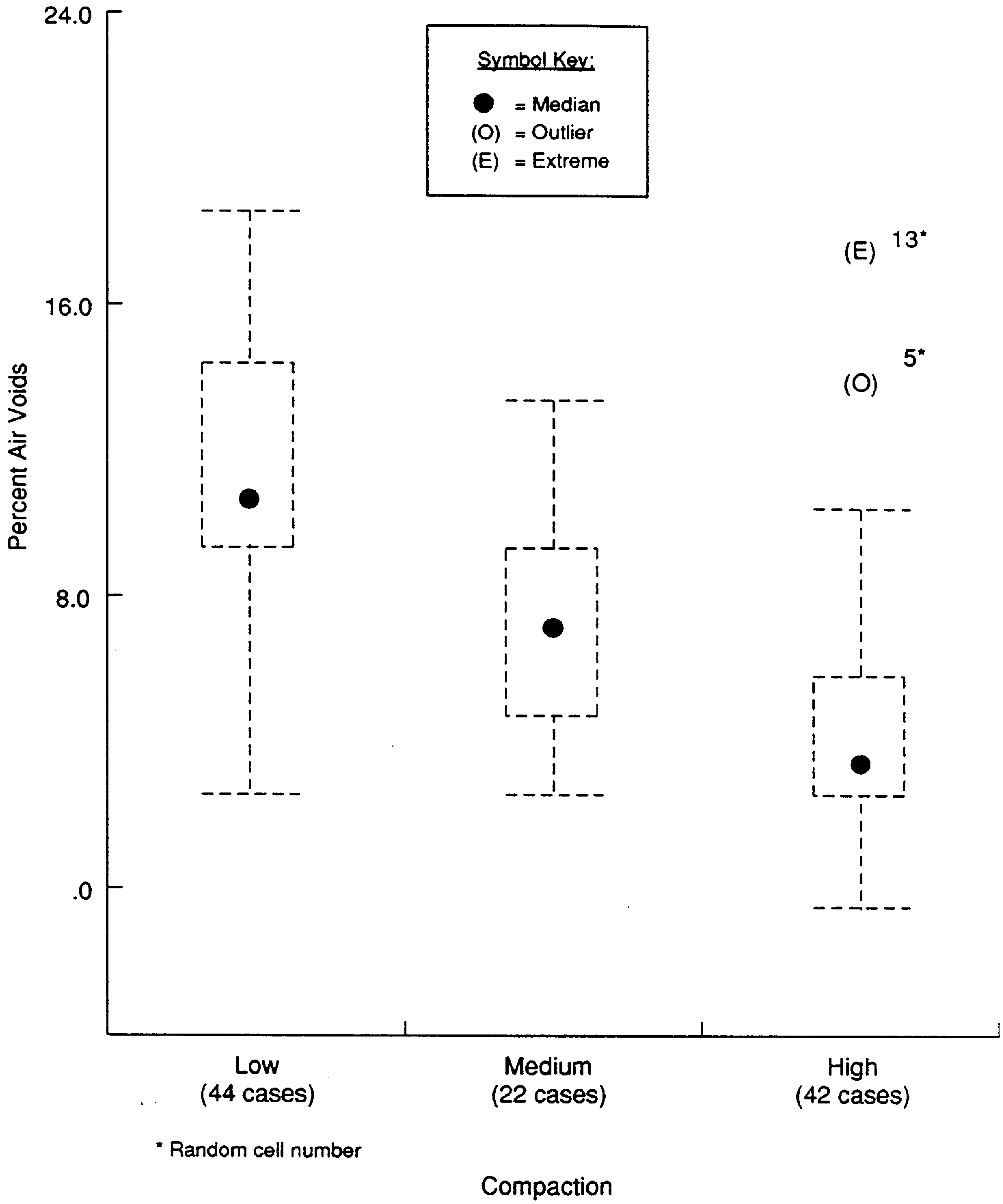


Figure 10. Distribution of percent air voids by compaction level.

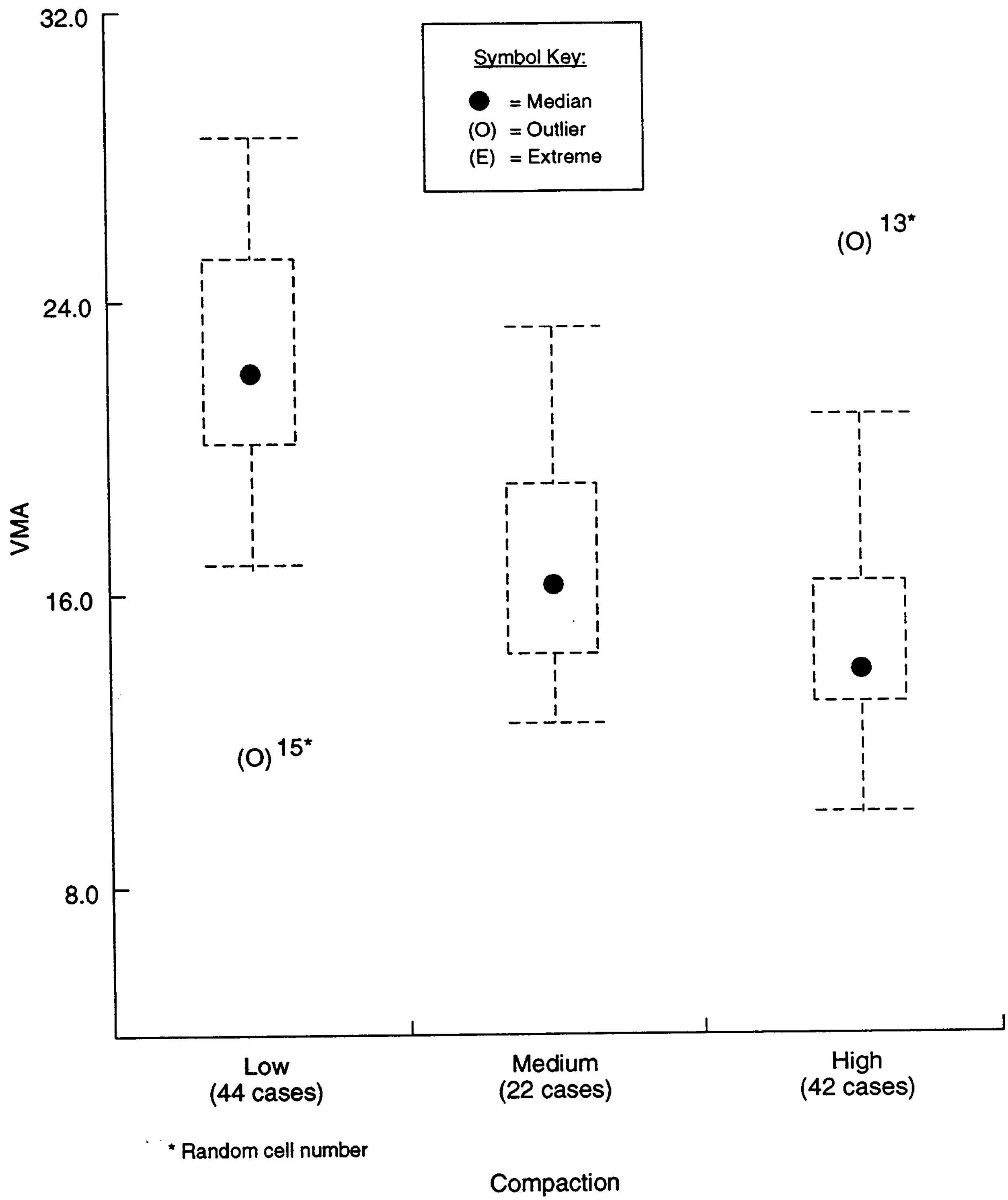


Figure 11. Distribution of VMA by compaction level.

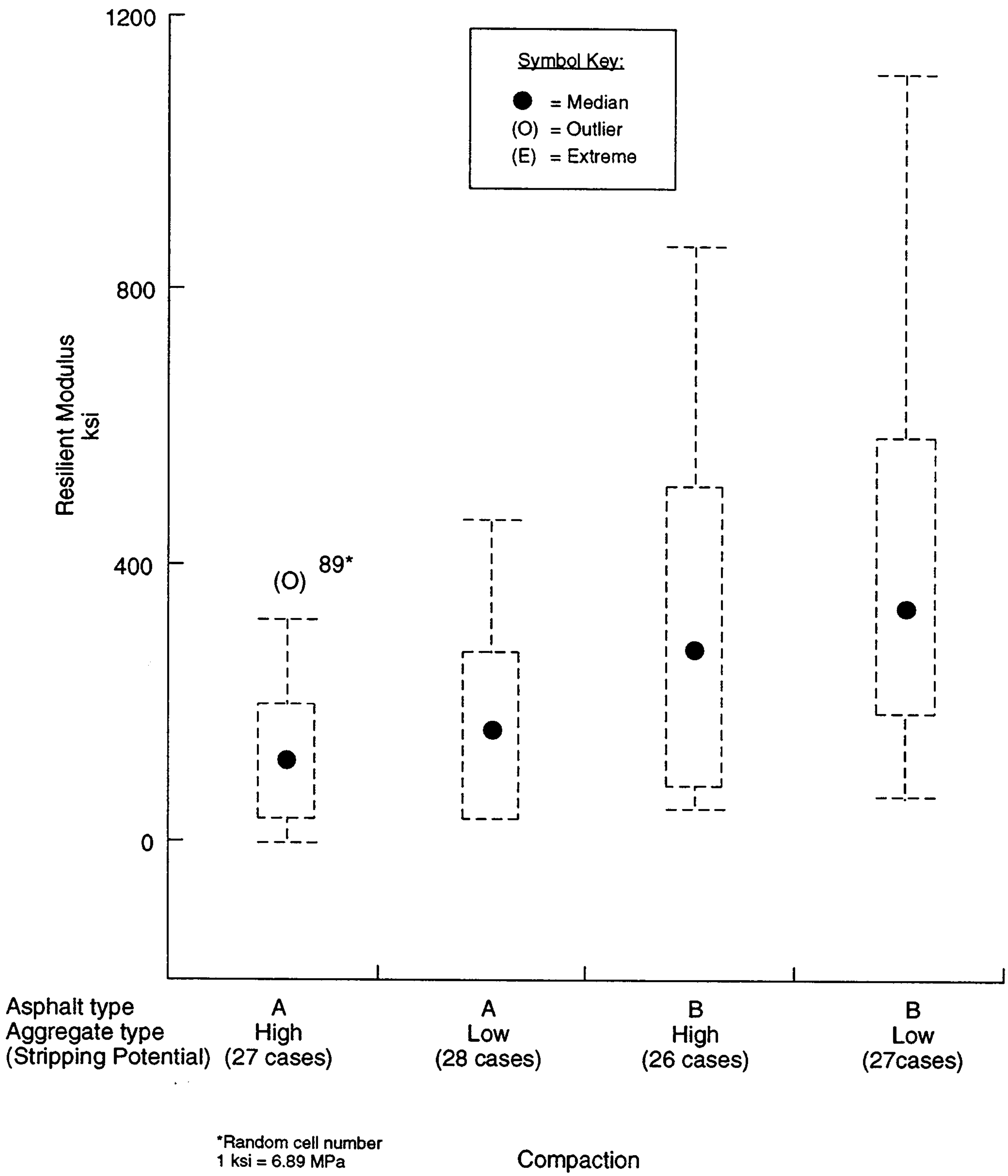


Figure 12. Distribution of resilient modulus values by asphalt type and aggregate type.

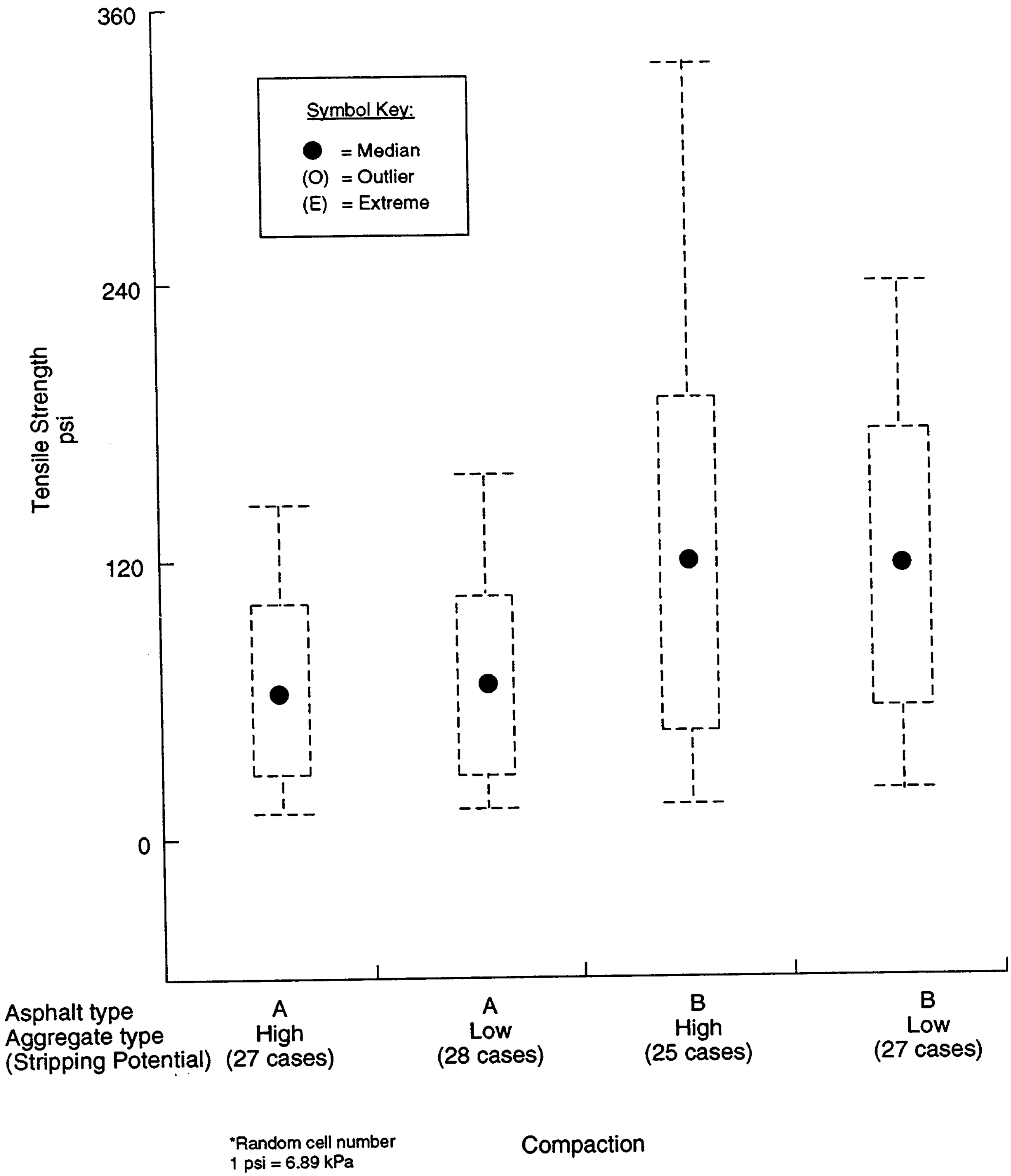


Figure 13. Distribution of tensile strength values by asphalt type and aggregate type.

Table 11. Final regression equations.

INDEPENDENT VARIABLE	EQUATION	N	R^2	SE
Compaction Index (CI)	2.19087-0.05206(VMA) - 0.23405(%VOIDS) + 0.00340623(%#30)(%VOIDS) - 0.02298(%#200)(%ASPHDEV) - 0.00882088(%#30)(%ASPHDEV)	105	0.85	0.34898
AC Type - ln (MR)	5.32928+0.64468(CI) + 0.94522(ASPHTYP) - 0.03965(VMA) + 0.02207(%ASPHDEV) - 0.26202(%ASPHDEV)^2 - 0.0012691(%#200) + 0.001484(%#200)(VMA)	108	0.84	0.38278
AC Type - ln (TS)	3.47901 + 0.74038(CI) + 0.51266(ASPHTYP) + 0.02932(VMA) + 0.12752(%ASPHDEV) - 0.15695(%ASPHDEV)^2 + 0.04984(%#200) - 0.001939(%#200)(VMA)	107	0.87	0.27457
AC Penetration - ln (MR)	7.60425 + 0.02189(%ASPHDEV) - 0.26264(%ASPHDEV)^2 - 0.02624(ASPHPEN) - 0.03926(VMA) + 0.64515(CI) - 0.000543256(%#200) + 0.001453686(%#200)(VMA)	108	0.84	0.38258
AC Penetration - ln (TS)	4.71325 + 0.12722(%ASPHDEV) - 0.15764(%ASPHDEV)^2 - 0.01423(ASPHPEN) + 0.02949(VMA) + 0.74065(CI) + 0.05005(%#200) - 0.00194589(%#200)(VMA)	107	0.87	0.27440
$\ln \left\{\frac{\text{MR (32 days)}}{\text{MR (1 day)}}\right\}$	0.18977 + 0.0020579(%#200)(VMA) - 0.01049(%ASPHDEV)(VMA) + 0.00046623(%#30)(VMA)	95	0.42	0.2307
$\ln \left\{\frac{\text{TS (32 days)}}{\text{TS (1 day)}}\right\}$	0.50560 - 0.0091774(CI)(%#30) - 0.0052624(VMA)	93	0.29	0.278
IRM	41.42601 - 69.58340(ADITV) + 34.55498(ASPHTYP)(ADITV) + 3.69456(VMA) + 28.91298(CI)(ADITV)	97	0.44	29.615
IRS	85.78256 - 1.52260(%#30)(ADITV) + 3.86562(ASPHTYP)(VMA) - 1.89002(ASPHTYP)(%#30)	96	0.37	35.608
log (NCYC)	2.92100 - 2.64601 log (S) + 2.22575 log (TS)	96	0.69	0.48751

%ASPHDEV	=	percent deviation from optimum asphalt content (percent)
%#30	=	percent passing No. 30 (600 μm) sieve (percent)
%#200	=	percent passing No. 200 (75 μm) sieve (percent)
ASPHTYP	=	asphalt type (temperature susceptibility) 0 = low and 1 = high
ASPHPEN	=	penetration value at 77 °F (25 °C)
ADITV	=	presence of lime 0 = yes and 1 = no
NCYC	=	Number of repetitions to failure
S	=	Applied stress level for fatigue analysis
N	=	Number of samples
R^2	=	Coefficient of determination
SE	=	Standard error

COMPACTION INDEX

As described in the previous chapter, the laboratory experiment was carried out with three levels of compaction. Each level represents the compaction effort applied to a sample and varies from low to medium to high. For this study, each compaction level has been assigned a numerical value (low = -1, medium = 0, and high = 1). The compaction variable defined above has been named Compaction Index (CI).

An equation for predicting compaction index from M&C variables was developed by a stepwise regression analysis, using the SPSS statistical analysis program.

First, all 108 data points were used to predict a CI equation. The software was set to the stepwise regression so that it would automatically select the most influential variables. The resulting equation was a function of air voids, VMA, asphalt content and several interactions of the variables. Among these variables, percent air voids and VMA were the most significant. As already indicated, the box plots for percent air voids (figure 11) and VMA (figure 12) show the presence of an extreme value (random cell 13) and two outliers (random cells 5 and 15). Therefore these data points were tested using Mahalanobis' and Cook's distances to determine how unusual and influential these data points were. It was found that all three data points had a large influence on estimates of the parameters. In addition, the extreme value (random cell 13) was found to be an unusual value. Based on these results, a decision was made to determine another regression equation for CI using only 105 data points. The resulting equation was:

$$CI = 2.19087 - 0.05206(VMA) - 0.23405(\%VOIDS) + 0.00340623(\%\#30)(\%VOIDS) - 0.02298(\%\#200)(\%ASPHDEV) - 0.00882088(\%\#30)(\%ASPHDEV) \tag{22}$$

with

$R^2 = 0.85459$
SE = 0.34898
N = 105

RESILIENT MODULUS 77 °F (25 °C)

An equation for predicting resilient modulus at 77 °F (25 °C) was obtained by using M&C variables found significant in the stepwise regression analysis. The resulting equation had more than 10 terms with some two-factor interactions not being quite significant. Therefore, a rerun was made to obtain a simplified equation for routine use which included main factors and only the most significant two-factor interactions. The simplification reduced the R-squares from 0.86 to 0.84 and increased the standard errors from 0.34923 to 0.38278.

The resulting equation was:

$$\ln MR = 5.32928 + 0.64468(CI) + 0.94522(ASPHTYP) - 0.03965(VMA) + 0.02207(\%ASPHDEV) - 0.26202(\%ASPHDEV)^2 - 0.0012691(\%\#200) + 0.001484(\%\#200)(VMA) \tag{23}$$

with

$R^2 = 0.84$
SE = 0.38278
N = 108

Another equation for MR was obtained using as a variable the penetration at 77 °F (25 °C) of each asphalt type, instead of the temperature susceptibility. The resulting equation was:

$$\ln MR = 7.60425 + 0.02189(\%ASPHDEV) - 0.26264(\%ASPHDEV)^2 - 0.02624(ASPHPEN) - 0.03926(VMA) + 0.64515(CI) - 0.000543256(\%\#200) + 0.001453686(\%\#200)(VMA) \tag{24}$$

with

$R^2 = 0.84$
SE = 0.38258
N = 108

TENSILE STRENGTH 77 °F (25 °C)

An equation for predicting tensile strength at 77 °F (25 °C) was produced by the same procedure used to develop the above modulus relationship. The equation developed by the stepwise regression analysis had an R-square of 0.92 and a standard error of 0.20999. A simplified equation was developed using the same variables as shown for MR; the simplification produced an R-square of 0.86 and a standard error of 0.27457.

The resulting equation was:

$$\ln TS = 3.47901 + 0.74038(CI) + 0.51266(ASPHTYP) + 0.02932(VMA) + 0.12752(\%ASPHDEV) - 0.15695(\%ASPHDEV)^2 + 0.04984(\%\#200) - 0.001939(\%\#200)(VMA) \tag{25}$$

with

$R^2 = 0.87$
SE = 0.27457
N = 108

Another equation for TS was obtained using as a variable the penetration at 77 °F (25 °C) of each asphalt type, instead of the temperature susceptibility. The resulting equation was:

$$\ln TS = 4.71325 + 0.12722(\%ASPHDEV) - 0.15764(\%ASPHDEV)^2 - 0.01423(ASPHPEN) + 0.02949(VMA) + 0.74065(CI) + 0.05005(\%\#200) - 0.00194589(\%\#200)(VMA) \qquad (26)$$

with

$R^2 = 0.87$
$SE = 0.27440$
$N = 108$

AGED-CONDITIONED RESILIENT MODULUS

An equation for predicting the ratio of aged-conditioned to unconditioned resilient modulus was produced by running a stepwise regression analysis. The resulting equation using the data from 95 samples had an R^2 of 0.422 and a standard error of 0.2307.

The resulting equation was:

$$\ln \frac{MR\ (32\ days)}{MR\ (1\ day)} = 0.18977 + 0.0020579(\%\#200)(VMA) - 0.01049(\%ASPHDEV)(VMA) + 0.00046623(\%\#30)(VMA) \qquad (27)$$

AGED-CONDITIONED TENSILE STRENGTH

An equation for predicting the ratio of aged-conditioned to unconditioned tensile strength was produced by the same procedure used to develop the above aged resilient modulus relationship. The resulting equation using the data from 93 samples had an R^2 of 0.285 and a standard error of 0.278.

The resulting equation was:

$$\ln \frac{TS\ (32\ days)}{TS\ (1\ day)} = 0.50560 - 0.0091774(CI)(\%\#30) - 0.0052624(VMA) \qquad (28)$$

MOISTURE-CONDITIONED SAMPLES

Several regression runs were performed using the index of retained modulus (IRM) and the index of retained strength (IRS). The developed equations were as follows:

$$IRM = 41.42601 - 69.58340(ADITV) + 34.55498(ASPHTYP)(ADITV) + 3.69456(VMA) + 28.91298(CI)(ADITV) \qquad (29)$$

with

$R^2 = 0.4403$
$SE = 29.615$
$N = 97$

$$IRS = 85.78256 - 1.52260(\%\#30)(ADITV) + 3.86562(ASPHTYP)(VMA) - 1.89002(ASPHTYP)(\%\#30) \quad (30)$$

with

$R^2 = 0.3747$
SE = 35.608
N = 96

The effect of moisture conditioning was not significant in the equations. Comparison of the developed equations with the listed secondary prediction relationships in table 4 shows that, for compaction index, resilient modulus, and tensile strength, the developed equations include several of the most significant M&C variables and have a high R^2.

FATIGUE LIFE

A stepwise regression analysis of the fatigue data yielded the following equation:

$$\text{Log NCYC} = 2.92100 - 2.64601\,(\text{Log S}) + 2.22575(\text{Log TS}) \quad (31)$$

with

$R^2 = 0.69$
SE = 0.48751
N = 48

This equation has been plotted in figure 14 for the two stresses used in the experiment: 12 psi (83 kPa) and 30 psi (207 kPa). As expected, both lines were parallel. The stress level of 12 psi (83 kPa) allows more cycles (11 times more) than the stress level of 30 psi (207 kPa).

PREDICTING VALUES OF THE DEPENDENT VARIABLES

The variability due to testing and inadequacies of the models would make it impractical to attempt to predict absolute values for any of the dependent variables. Accordingly, the application of the prediction equations has to be based on ratios of actual predicted values to values predicted for optimum materials and construction conditions.

The formula for predicting relative mixture properties is as follows:

$$\text{Adjusted value} = \frac{\text{Prediction equation for actual conditions}}{\text{Predicted value for optimum conditions}} \quad (32)$$

For the materials and test conditions of this study, optimum conditions are described by:

CI = 1
Asphalt type = 0
Asphalt content deviation = 0
Aggregate type = 0
Passing #200 sieve = 7.1%

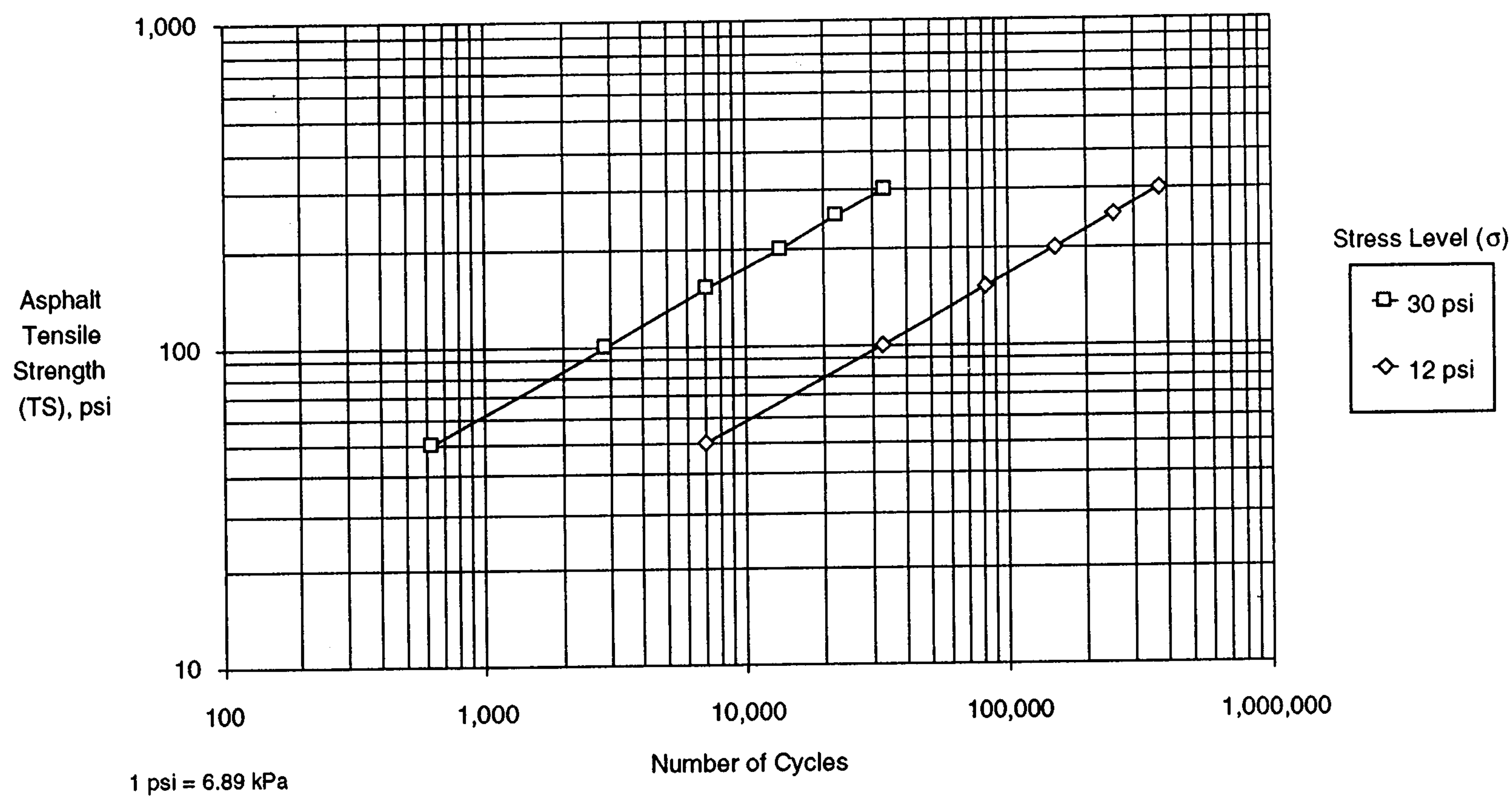


Figure 14. Effect of asphalt tensile strength and stress level on asphalt fatigue life.

Passing #30 sieve = 18.1%
VMA = 14.4%
Antistrip additive = 0

In practice, optimum conditions will be defined as those conditions for which the contracting agency would be wiling to pay 100 percent of the contract price.

GRAPHICAL PRESENTATIONS OF RELATIVE EFFECTS

The above equations have been solved for a range of conditions, and tabulated and plotted to show effects of different M&C variables on MR and TS. Tabulated values are included in tables 12 through 15 and plots are presented in figures 15 through 25. The graphs show the effects of compaction, VMA, and other M&C variables on performance-related mixture properties. Optimum conditions were calculated as described in the previous section.

The first three columns in table 12 represent the effect of the percent asphalt deviation on the ratio of predicted to optimum resilient modulus (M_r/M_ropt). The three columns in the middle represent the effect of the compaction index (CI), and the last three columns represent the effect of the percent passing No. 200 (75 μm). In all three cases the values of M_r and M_r/M_ropt have been calculated for VMA values varying from 2 to 32 in increments of two. The calculations for M_r were done using equation (23). The results for these three cases have been plotted in figures 15, 16, and 17, respectively.

Figure 15 shows the effect of VMA, and percent asphalt deviation from optimum. An increase or decrease in asphalt content causes a reduction in resilient modulus. In this particular case an increase or decrease of 0.75 percent asphalt content causes an average reduction of 14 percent on M_r values. This decrease is constant at all levels of VMA. Also, as the percent VMA increases, the M_r values decrease. The decrease in M_r is nonlinear.

Figure 16 shows the effect of VMA and compaction index on M_r/M_ropt. The resilient modulus increases with an increase in compaction effort. The values in table 12 corresponding to CI indicate that the increase or decrease in M_r values corresponding to a change in compactive effort is the same for all percentages of VMA.

Figure 17 shows the effect of percent passing sieve No. 200 (75 μm) on M_r/M_ropt. For the three values selected in this study (0, 6, and 12 percent), M_r values increase as the percent passing increases. This effect of the percent passing No. 200 (75 μm) is less significant at low values of VMA (less than 10 percent) and more significant at higher values of VMA (greater than 20 percent). The effect of VMA on M_r increases as the percent passing decreases. For example, using the values in table 12, a change from 10 to 12 percent VMA for a 12-percent passing causes a 4.3-percent reduction in M_r, while for 0-percent passing the same change in VMA causes a reduction of 6.8 percent.

Table 12. Effect of M&C variables on the ratio of predicted to optimum resilient modulus.

	% Asphalt						CI						% #200					
	-0.75		0		0.75		-1		0		1		0		6		12	
VMA	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt	Mr	Mr/MrOpt
2	311.9	1.2178	367.5	1.4348	322.4	1.2588	101.2	0.3952	192.9	0.7530	367.5	1.4348	363.1	1.4176	366.8	1.4321	370.6	1.4468
4	294.3	1.1489	346.7	1.3536	304.2	1.1876	95.5	0.3729	182.0	0.7104	346.7	1.3536	335.4	1.3095	344.9	1.3467	354.7	1.3849
6	277.6	1.0840	327.1	1.2771	287.0	1.1204	90.1	0.3518	171.7	0.6702	327.1	1.2771	309.8	1.2097	324.4	1.2664	339.6	1.3257
8	261.9	1.0226	308.6	1.2048	270.8	1.0571	85.0	0.3319	162.0	0.6323	308.6	1.2048	286.2	1.1174	305.0	1.1908	325.1	1.2691
10	247.1	0.9648	291.1	1.1367	255.4	0.9973	80.2	0.3131	152.8	0.5966	291.1	1.1367	264.4	1.0323	286.8	1.1198	311.2	1.2148
12	233.1	0.9102	274.7	1.0724	241.0	0.9409	75.7	0.2954	144.2	0.5628	274.7	1.0724	244.2	0.9536	269.7	1.0530	297.9	1.1629
14	220.0	0.8587	259.1	1.0117	227.4	0.8876	71.4	0.2787	136.0	0.5310	259.1	1.0117	225.6	0.8809	253.6	0.9902	285.1	1.1132
16	207.5	0.8102	244.5	0.9545	214.5	0.8374	67.3	0.2629	128.3	0.5009	244.5	0.9545	208.4	0.8137	238.5	0.9312	272.9	1.0656
18	195.8	0.7643	230.7	0.9005	202.4	0.7901	63.5	0.2480	121.1	0.4726	230.7	0.9005	192.5	0.7517	224.3	0.8756	261.3	1.0201
20	184.7	0.7211	217.6	0.8496	190.9	0.7454	59.9	0.2340	114.2	0.4459	217.6	0.8496	177.9	0.6944	210.9	0.8234	250.1	0.9765
22	174.3	0.6803	205.3	0.8015	180.1	0.7032	56.5	0.2208	107.7	0.4207	205.3	0.8015	164.3	0.6414	198.3	0.7743	239.4	0.9347
24	164.4	0.6418	193.7	0.7562	169.9	0.6634	53.3	0.2083	101.7	0.3969	193.7	0.7562	151.8	0.5925	186.5	0.7281	229.2	0.8948
26	155.1	0.6055	182.7	0.7134	160.3	0.6259	50.3	0.1965	95.9	0.3744	182.7	0.7134	140.2	0.5474	175.4	0.6847	219.4	0.8565
28	146.3	0.5713	172.4	0.6730	151.3	0.5905	47.5	0.1854	90.5	0.3532	172.4	0.6730	129.5	0.5056	164.9	0.6439	210.0	0.8199
30	138.0	0.5390	162.6	0.6350	142.7	0.5571	44.8	0.1749	85.4	0.3333	162.6	0.6350	119.6	0.4671	155.1	0.6055	201.0	0.7849
32	130.2	0.5085	153.4	0.5991	134.6	0.5256	42.3	0.1650	80.5	0.3144	153.4	0.5991	110.5	0.4315	145.8	0.5694	192.4	0.7513

sieve #200 = 75 μm
1 ksi = 6.89 MPa

Table 13. Effect of M&C variables on the ratio of predicted to optimum tensile strength.

	% Asphalt						CI						% #200					
	-0.75		0		0.75		-1		0		1		0		6		12	
VMA	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp	TS	TS/TSOp
2	73.933	1.4195	88.862	1.7062	89.518	1.7188	20.213	0.3881	42.381	0.8137	88.862	1.7062	64.120	1.2311	84.481	1.6221	111.31	2.1372
4	67.829	1.3023	81.525	1.5653	82.127	1.5769	18.544	0.3561	38.882	0.7466	81.525	1.5653	60.468	1.1610	77.837	1.4945	100.20	1.9238
6	62.229	1.1948	74.794	1.4361	75.346	1.4467	17.013	0.3267	35.672	0.6849	74.794	1.4361	57.024	1.0949	71.716	1.3770	90.19	1.7318
8	57.091	1.0962	68.619	1.3175	69.126	1.3272	15.608	0.2997	32.727	0.6284	68.619	1.3175	53.776	1.0325	66.076	1.2687	81.19	1.5589
10	52.377	1.0057	62.954	1.2087	63.418	1.2177	14.320	0.2749	30.025	0.5765	62.954	1.2087	50.713	0.9737	60.880	1.1689	73.08	1.4032
12	48.053	0.9226	57.756	1.1089	58.182	1.1171	13.137	0.2522	27.546	0.5289	57.756	1.1089	47.825	0.9183	56.092	1.0770	65.79	1.2632
14	44.086	0.8465	52.988	1.0174	53.379	1.0249	12.053	0.2314	25.272	0.4852	52.988	1.0174	45.101	0.8660	51.681	0.9923	59.22	1.1371
16	40.446	0.7766	48.613	0.9334	48.972	0.9403	11.058	0.2123	23.185	0.4452	48.613	0.9334	42.533	0.8166	47.617	0.9143	53.31	1.0236
18	37.106	0.7125	44.599	0.8563	44.928	0.8626	10.145	0.1948	21.271	0.4084	44.599	0.8563	40.110	0.7701	43.872	0.8424	47.99	0.9214
20	34.043	0.6536	40.917	0.7856	41.219	0.7914	9.307	0.1787	19.515	0.3747	40.917	0.7856	37.826	0.7263	40.422	0.7761	43.20	0.8294
22	31.232	0.5997	37.539	0.7208	37.816	0.7261	8.539	0.1639	17.903	0.3438	37.539	0.7208	35.671	0.6849	37.243	0.7151	38.88	0.7466
24	28.654	0.5502	34.439	0.6613	34.694	0.6661	7.834	0.1504	16.425	0.3154	34.439	0.6613	33.640	0.6459	34.314	0.6588	35.00	0.6721
26	26.288	0.5047	31.596	0.6067	31.829	0.6111	7.187	0.1380	15.069	0.2893	31.596	0.6067	31.724	0.6091	31.616	0.6070	31.51	0.6050
28	24.117	0.4631	28.987	0.5566	29.201	0.5607	6.594	0.1266	13.825	0.2654	28.987	0.5566	29.917	0.5744	29.130	0.5593	28.36	0.5446
30	22.126	0.4248	26.594	0.5106	26.790	0.5144	6.049	0.1161	12.684	0.2435	26.594	0.5106	28.213	0.5417	26.839	0.5153	25.53	0.4902
32	20.299	0.3898	24.398	0.4685	24.579	0.4719	5.550	0.1066	11.636	0.2234	24.398	0.4685	26.606	0.5109	24.728	0.4748	22.98	0.4413

sieve #200 = 75 μm
1 psi = 6.89 kPa

Table 14. Effect of M&C variables on the ratio of predicted to optimum aged resilient modulus.

	% Asphalt						% #30						% #200					
	-0.75		0		0.75		12		17		30		0		6		12	
VMA	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index	AGMRR	Index
2	1.286	0.7633	1.266	0.7514	1.246	0.7397	1.259	0.7471	1.265	0.7506	1.280	0.7598	1.230	0.7298	1.260	0.7480	1.292	0.7667
4	1.368	0.8120	1.326	0.7868	1.285	0.7625	1.311	0.7779	1.323	0.7852	1.355	0.8045	1.250	0.7422	1.314	0.7798	1.380	0.8192
6	1.455	0.8638	1.388	0.8240	1.324	0.7860	1.365	0.8100	1.384	0.8214	1.435	0.8519	1.272	0.7548	1.370	0.8129	1.475	0.8754
8	1.548	0.9189	1.454	0.8628	1.365	0.8102	1.421	0.8434	1.448	0.8593	1.520	0.9020	1.293	0.7677	1.428	0.8474	1.576	0.9353
10	1.647	0.9775	1.522	0.9036	1.407	0.8352	1.480	0.8782	1.515	0.8989	1.609	0.9551	1.315	0.7807	1.488	0.8833	1.684	0.9994
12	1.752	1.0399	1.594	0.9462	1.451	0.8609	1.541	0.9144	1.584	0.9404	1.704	1.0113	1.338	0.7940	1.551	0.9208	1.799	1.0679
14	1.864	1.1062	1.669	0.9908	1.495	0.8875	1.604	0.9521	1.657	0.9837	1.804	1.0709	1.361	0.8075	1.617	0.9599	1.923	1.1411
16	1.983	1.1768	1.748	1.0376	1.541	0.9148	1.670	0.9914	1.734	1.0291	1.910	1.1339	1.384	0.8213	1.686	1.0007	2.054	1.2192
18	2.109	1.2518	1.831	1.0865	1.589	0.9431	1.739	1.0323	1.814	1.0765	2.023	1.2006	1.407	0.8353	1.758	1.0431	2.195	1.3028
20	2.244	1.3317	1.917	1.1378	1.638	0.9721	1.811	1.0749	1.897	1.1262	2.142	1.2713	1.431	0.8495	1.832	1.0874	2.345	1.3920
22	2.387	1.4166	2.007	1.1915	1.688	1.0021	1.886	1.1192	1.985	1.1781	2.268	1.3461	1.456	0.8639	1.910	1.1336	2.506	1.4874
24	2.539	1.5070	2.102	1.2477	1.740	1.0330	1.963	1.1654	2.076	1.2324	2.402	1.4254	1.480	0.8786	1.991	1.1817	2.678	1.5893
26	2.701	1.6031	2.201	1.3065	1.794	1.0648	2.044	1.2134	2.172	1.2892	2.543	1.5093	1.506	0.8936	2.076	1.2319	2.861	1.6982
28	2.873	1.7053	2.305	1.3682	1.849	1.0977	2.129	1.2634	2.272	1.3487	2.693	1.5981	1.531	0.9088	2.164	1.2841	3.057	1.8145
30	3.057	1.8141	2.414	1.4327	1.906	1.1315	2.217	1.3156	2.377	1.4108	2.851	1.6922	1.557	0.9243	2.255	1.3387	3.267	1.9388
32	3.252	1.9298	2.528	1.5003	1.965	1.1664	2.308	1.3698	2.487	1.4759	3.019	1.7918	1.584	0.9400	2.351	1.3955	3.490	2.0717

Sieve #30 = 600 µm
Sieve #200 = 75 µm

Table 15. Effect of M&C variables on the ratio of predicted to optimum aged indirect tensile strength.

	% #30						CI					
	12		17		30		-1		0		1	
VMA %	AGTSR	Index	AGTSR	Index	AGTSR	Index	AGTSR	Index	AGTSR	Index	AGTSR	Index
2	0.3849	1.4597	0.3391	1.2857	0.2198	0.8333	0.6612	2.5072	0.4951	1.8773	0.3290	1.2474
4	0.3744	1.4198	0.3285	1.2458	0.2092	0.7934	0.6507	2.4673	0.4846	1.8374	0.3184	1.2075
6	0.3639	1.3799	0.3180	1.2059	0.1987	0.7535	0.6401	2.4274	0.4740	1.7975	0.3079	1.1676
8	0.3534	1.3400	0.3075	1.1660	0.1882	0.7136	0.6296	2.3875	0.4635	1.7576	0.2974	1.1277
10	0.3428	1.3001	0.2970	1.1261	0.1777	0.6737	0.6191	2.3476	0.4530	1.7177	0.2869	1.0878
12	0.3323	1.2602	0.2864	1.0862	0.1671	0.6338	0.6086	2.3077	0.4425	1.6778	0.2763	1.0479
14	0.3218	1.2203	0.2759	1.0463	0.1566	0.5938	0.5980	2.2678	0.4319	1.6379	0.2658	1.0080
16	0.3113	1.1804	0.2654	1.0064	0.1461	0.5539	0.5875	2.2279	0.4214	1.5980	0.2553	0.9681
18	0.3007	1.1404	0.2549	0.9664	0.1356	0.5140	0.5770	2.1880	0.4109	1.5581	0.2448	0.9282
20	0.2902	1.1005	0.2443	0.9265	0.1250	0.4741	0.5665	2.1480	0.4004	1.5181	0.2342	0.8883
22	0.2797	1.0606	0.2338	0.8866	0.1145	0.4342	0.5559	2.1081	0.3898	1.4782	0.2237	0.8483
24	0.2692	1.0207	0.2233	0.8467	0.1040	0.3943	0.5454	2.0682	0.3793	1.4383	0.2132	0.8084
26	0.2586	0.9808	0.2128	0.8068	0.0935	0.3544	0.5349	2.0283	0.3688	1.3984	0.2027	0.7685
28	0.2481	0.9409	0.2022	0.7669	0.0829	0.3145	0.5244	1.9884	0.3583	1.3585	0.1921	0.7286
30	0.2376	0.9010	0.1917	0.7270	0.0724	0.2746	0.5138	1.9485	0.3477	1.3186	0.1816	0.6887
32	0.2271	0.8611	0.1812	0.6871	0.0619	0.2347	0.5033	1.9086	0.3372	1.2787	0.1711	0.6488

Sieve #30 = 600 μm

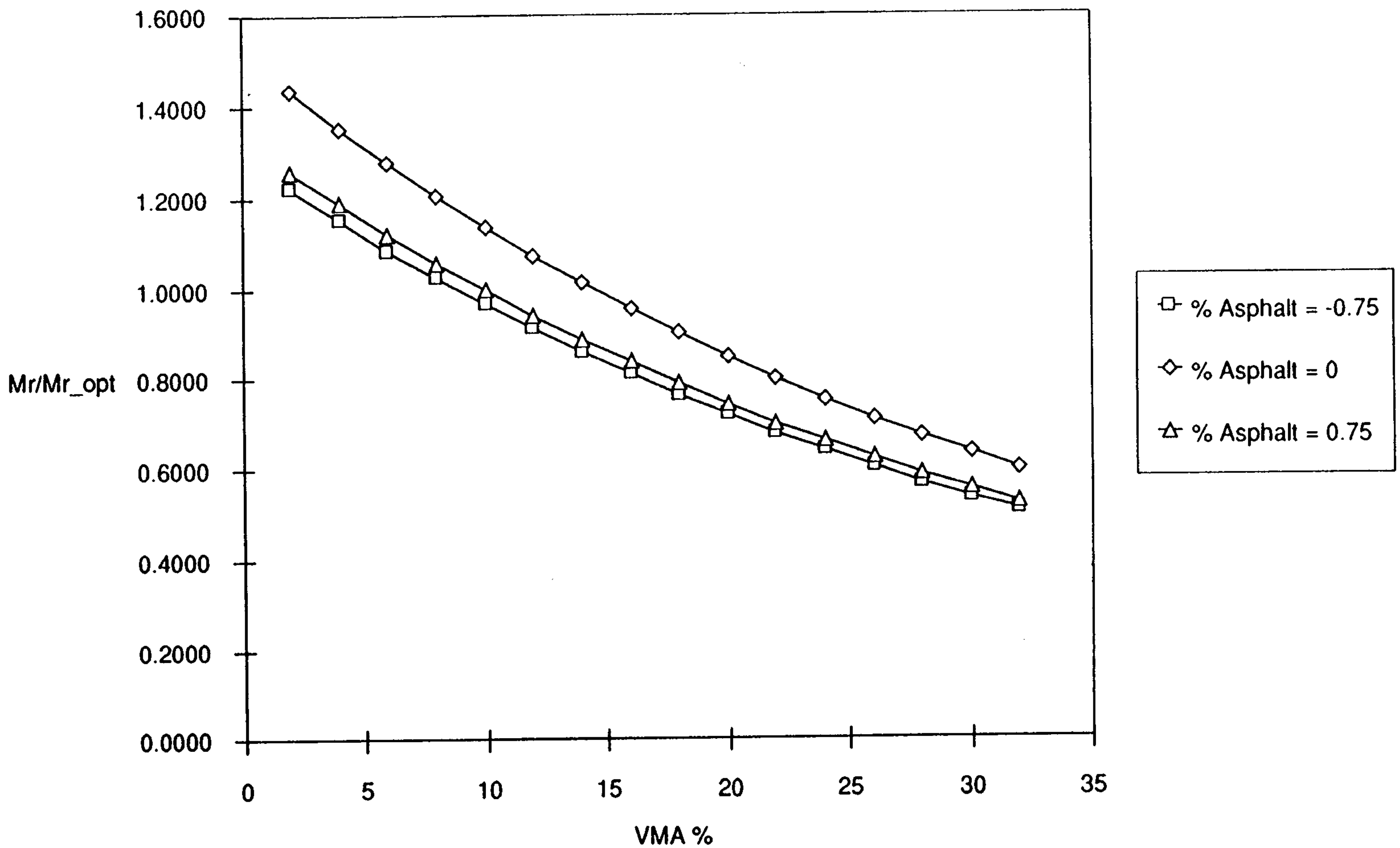


Figure 15. Effect of VMA and percent asphalt deviation on the ratio of predicted to optimum resilient modulus.

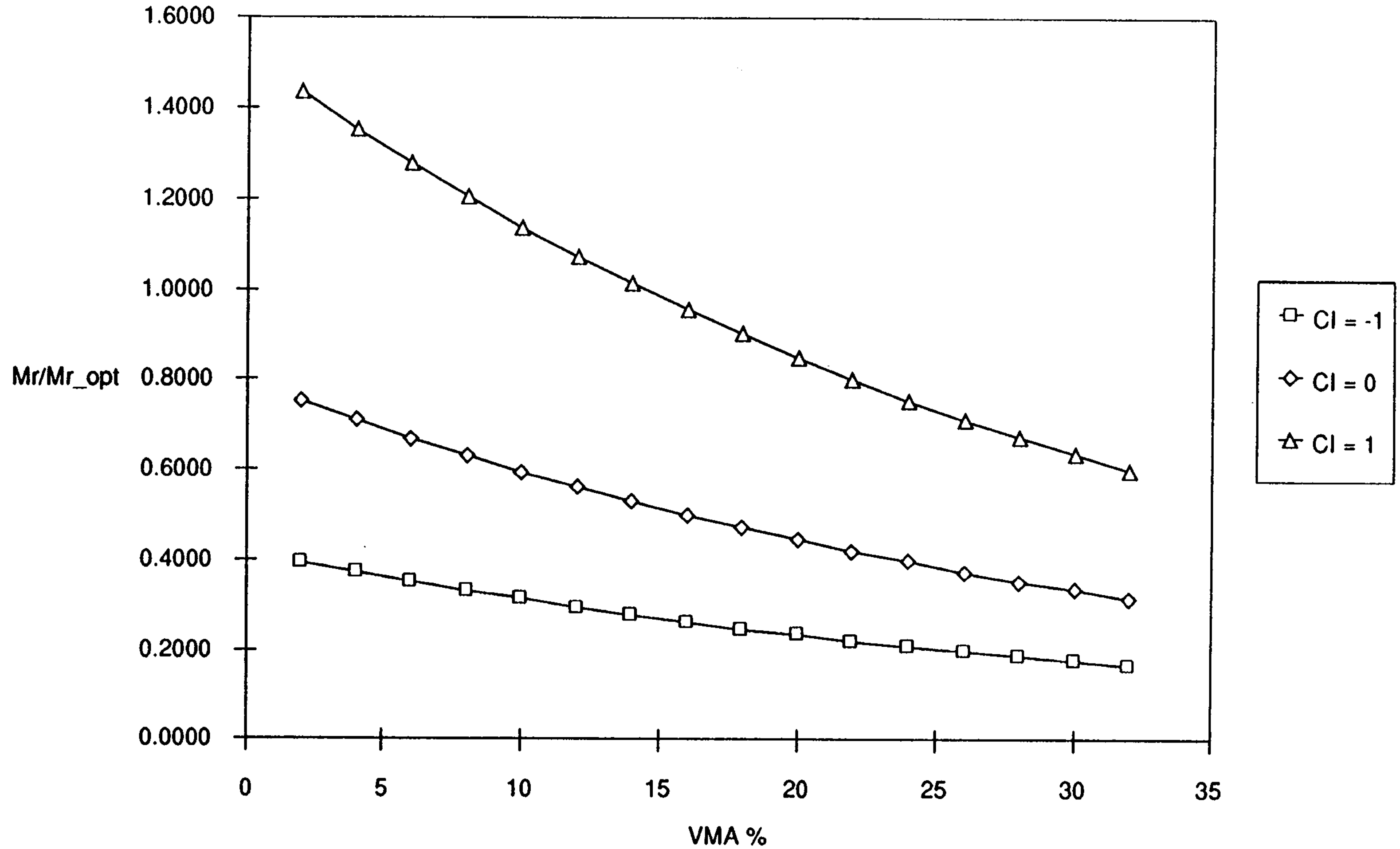


Figure 16. Effect of VMA and compaction index on the ratio of predicted to optimum resilient modulus.

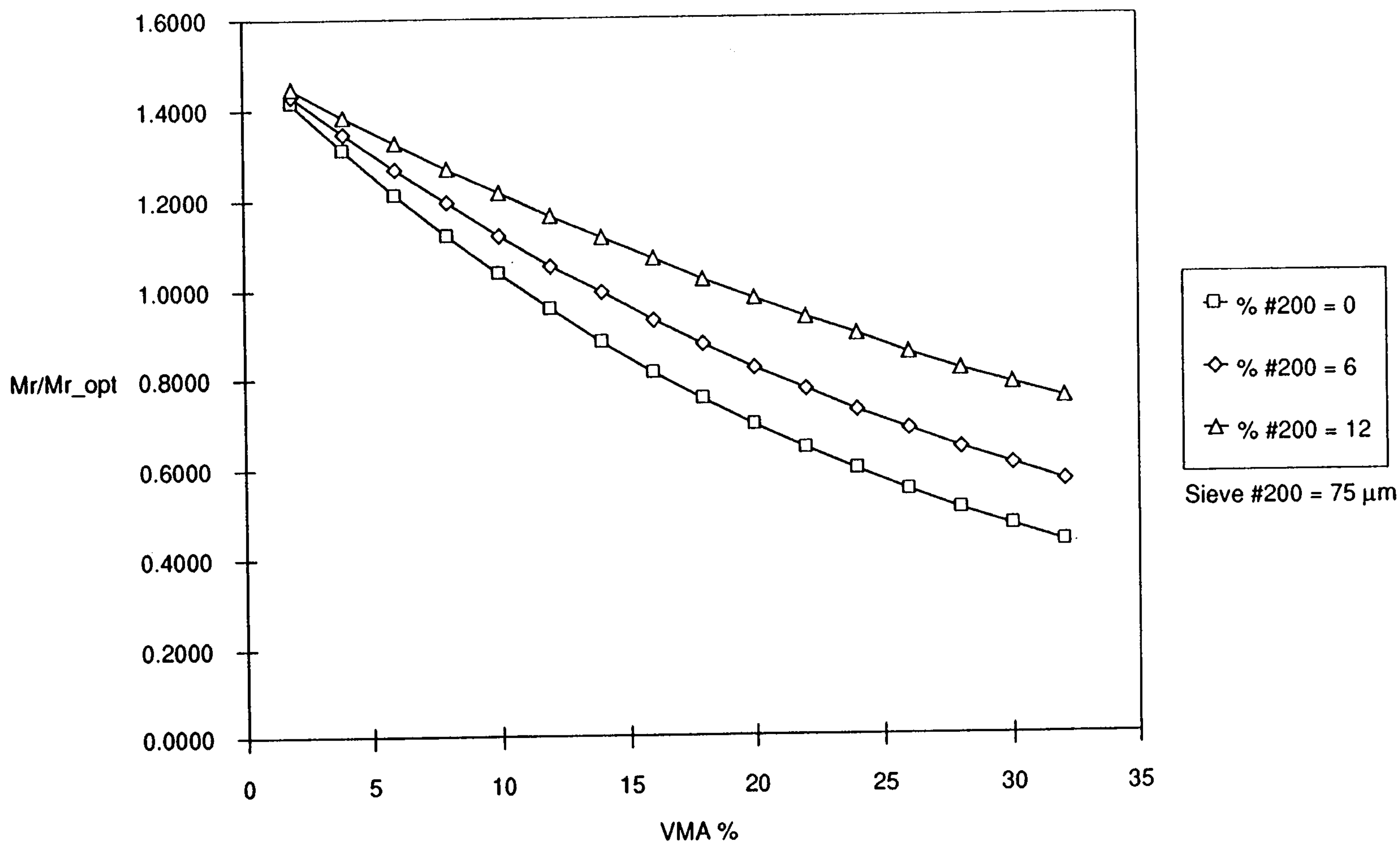


Figure 17. Effect of VMA and percent passing sieve #200 on the ratio of predicted to optimum resilient modulus.

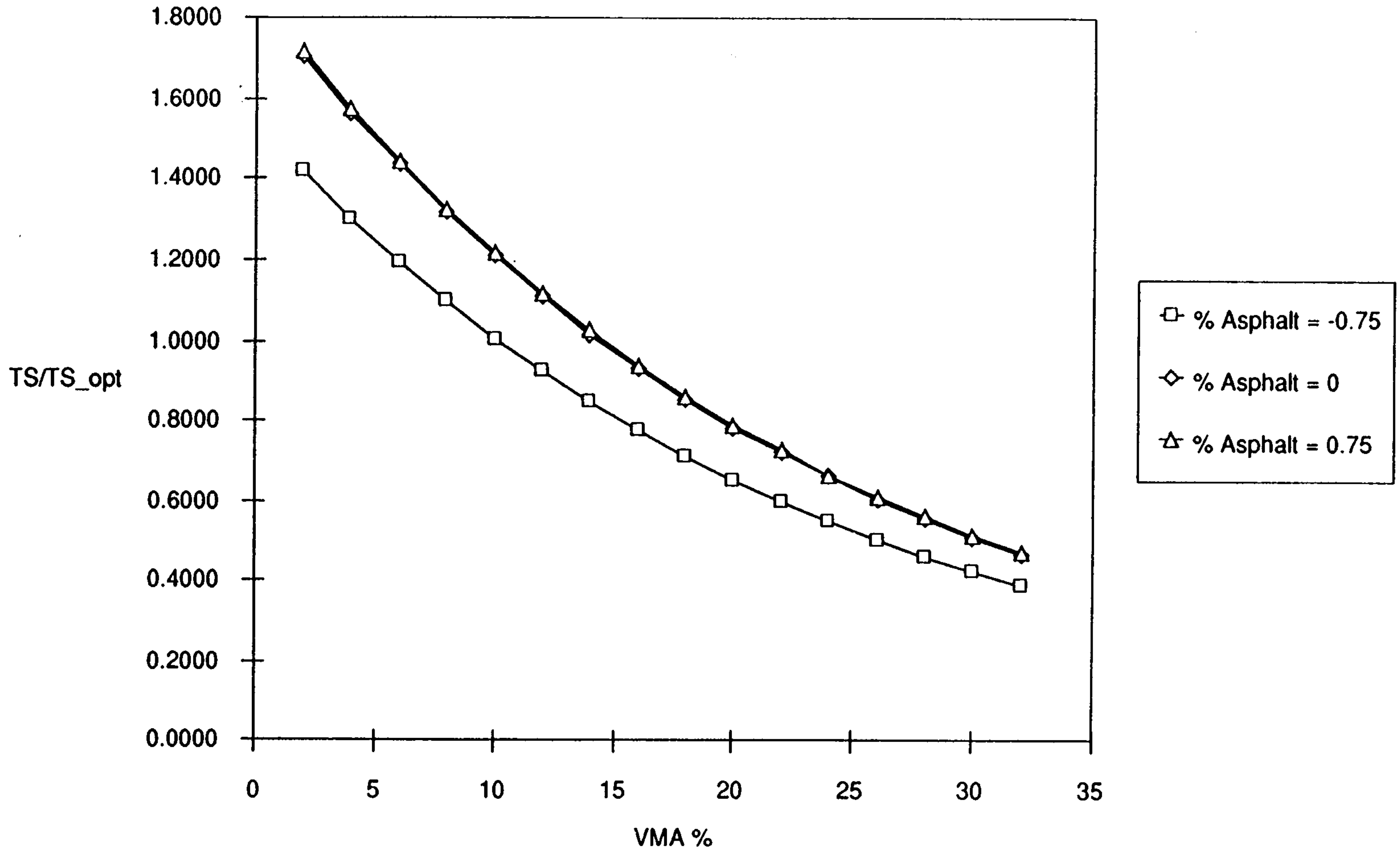


Figure 18. Effect of VMA and percent asphalt deviation on the ratio of predicted to optimum indirect tensile strength.

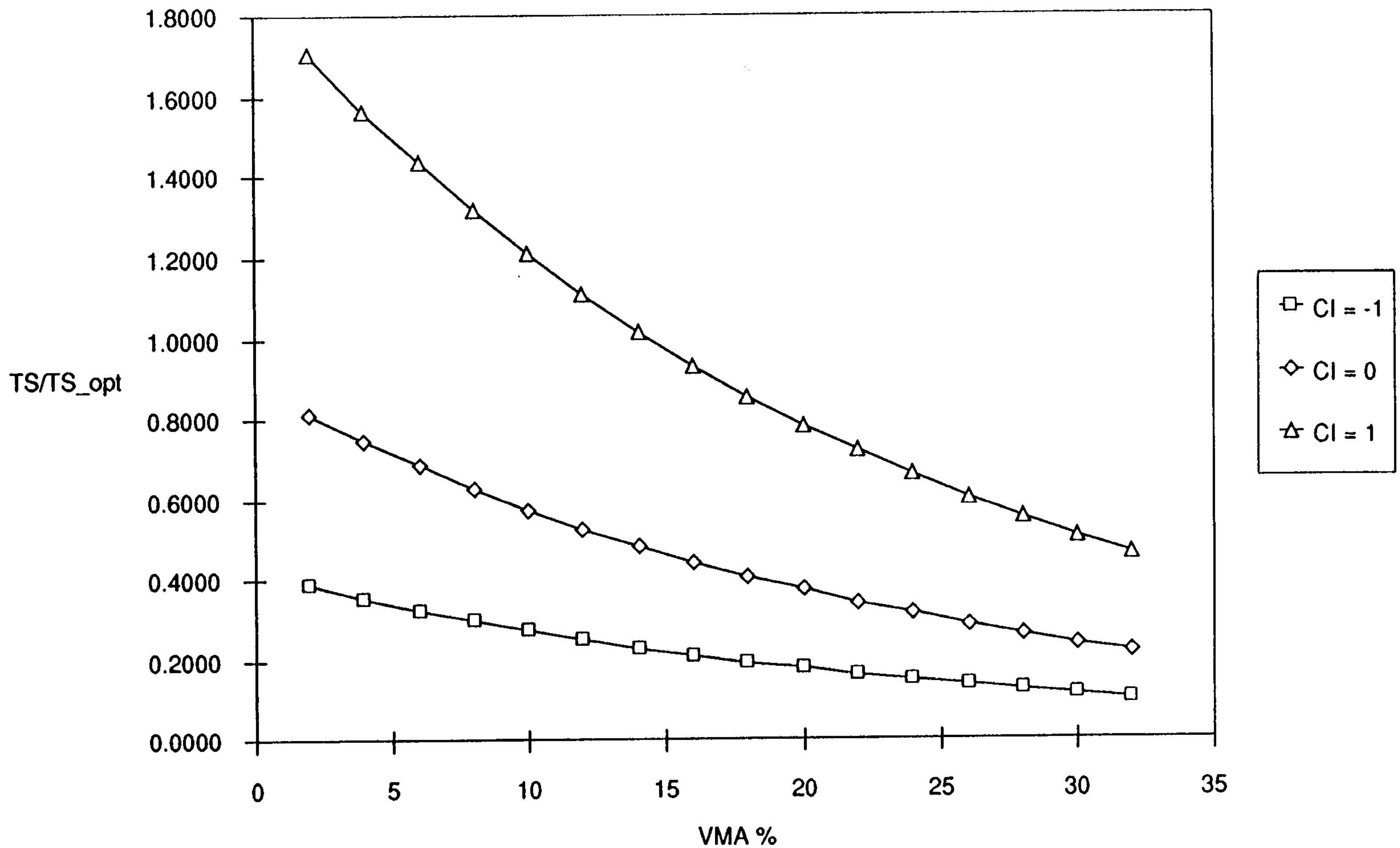


Figure 19. Effect of VMA and compaction index on the ratio of predicted to optimum indirect tensile strength.

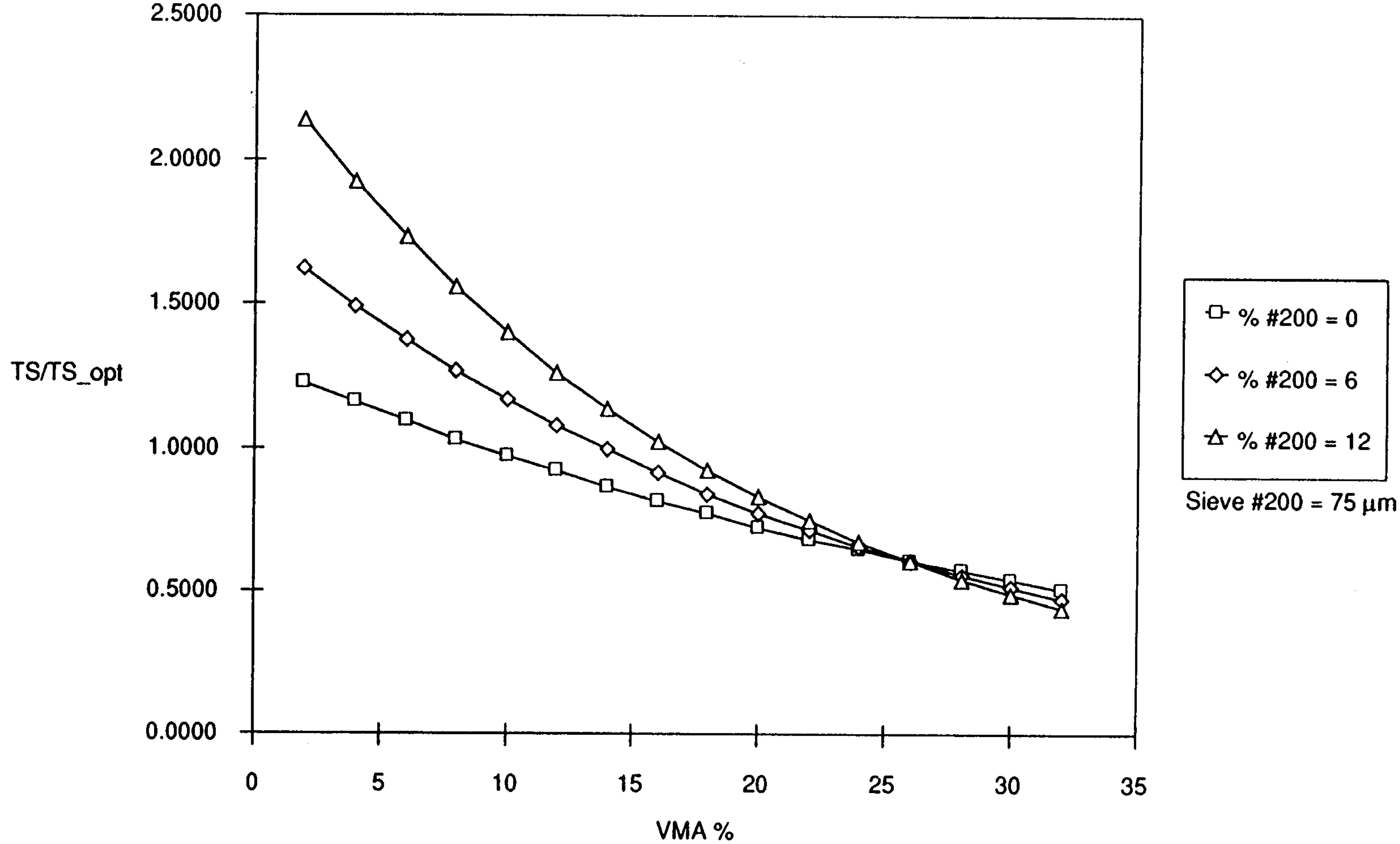


Figure 20. Effect of VMA and percent passing sieve #200 on the ratio of predicted to optimum indirect tensile strength.

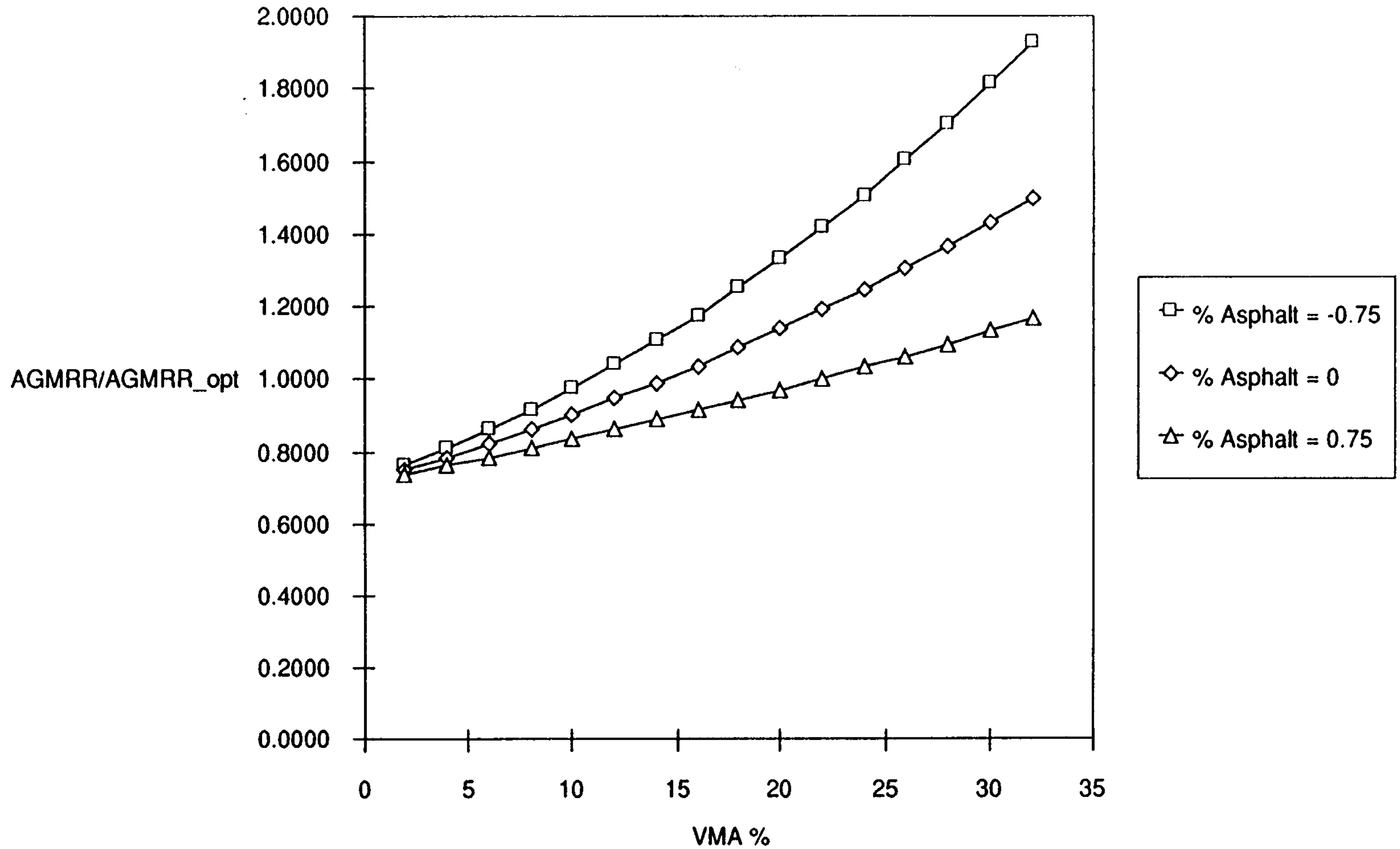


Figure 21. Effect of VMA and percent asphalt deviation on the ratio of predicted to optimum aged resilient modulus.

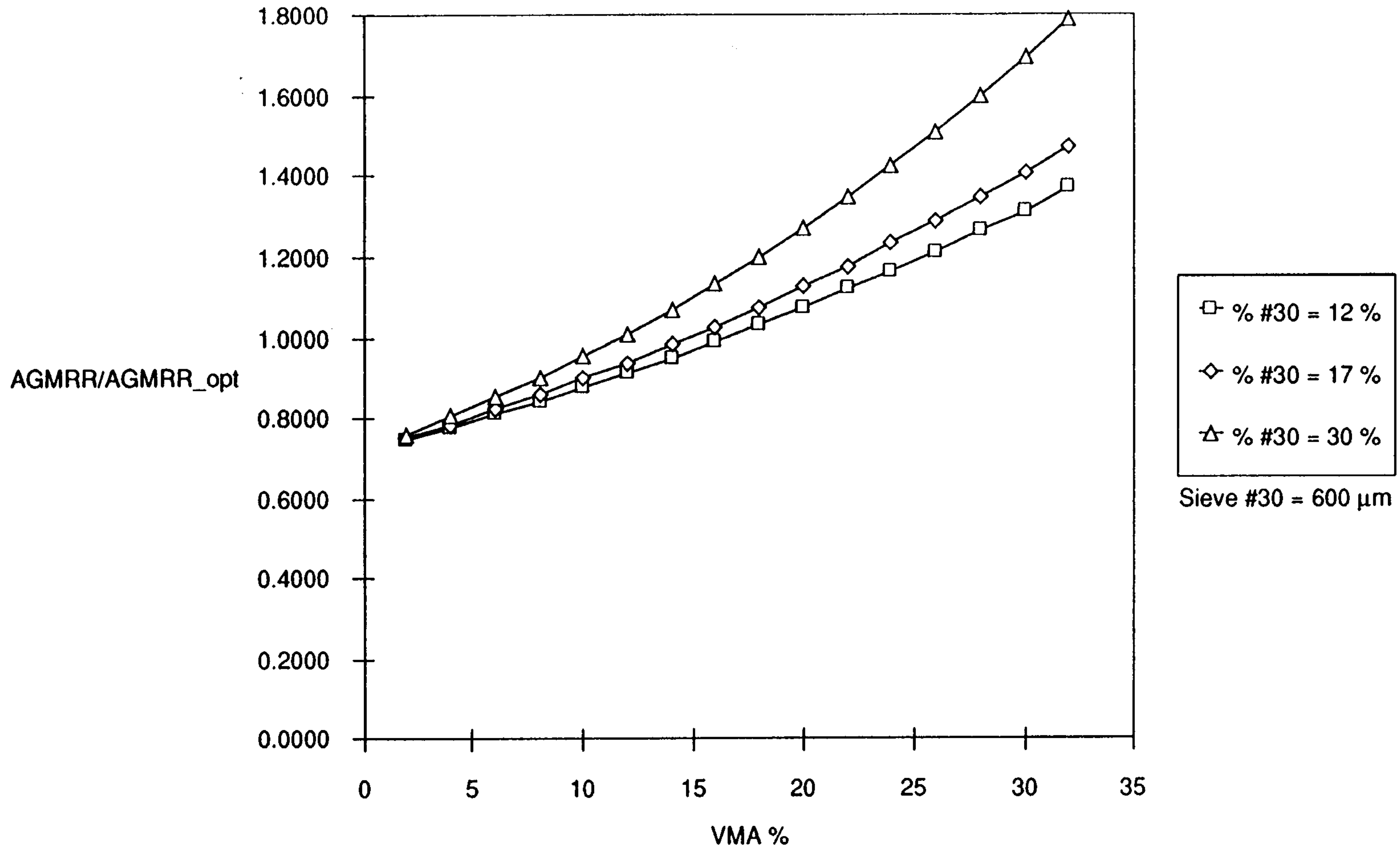


Figure 22. Effect of VMA and percent passing sieve #30 on the ratio of predicted to optimum aged resilient modulus.

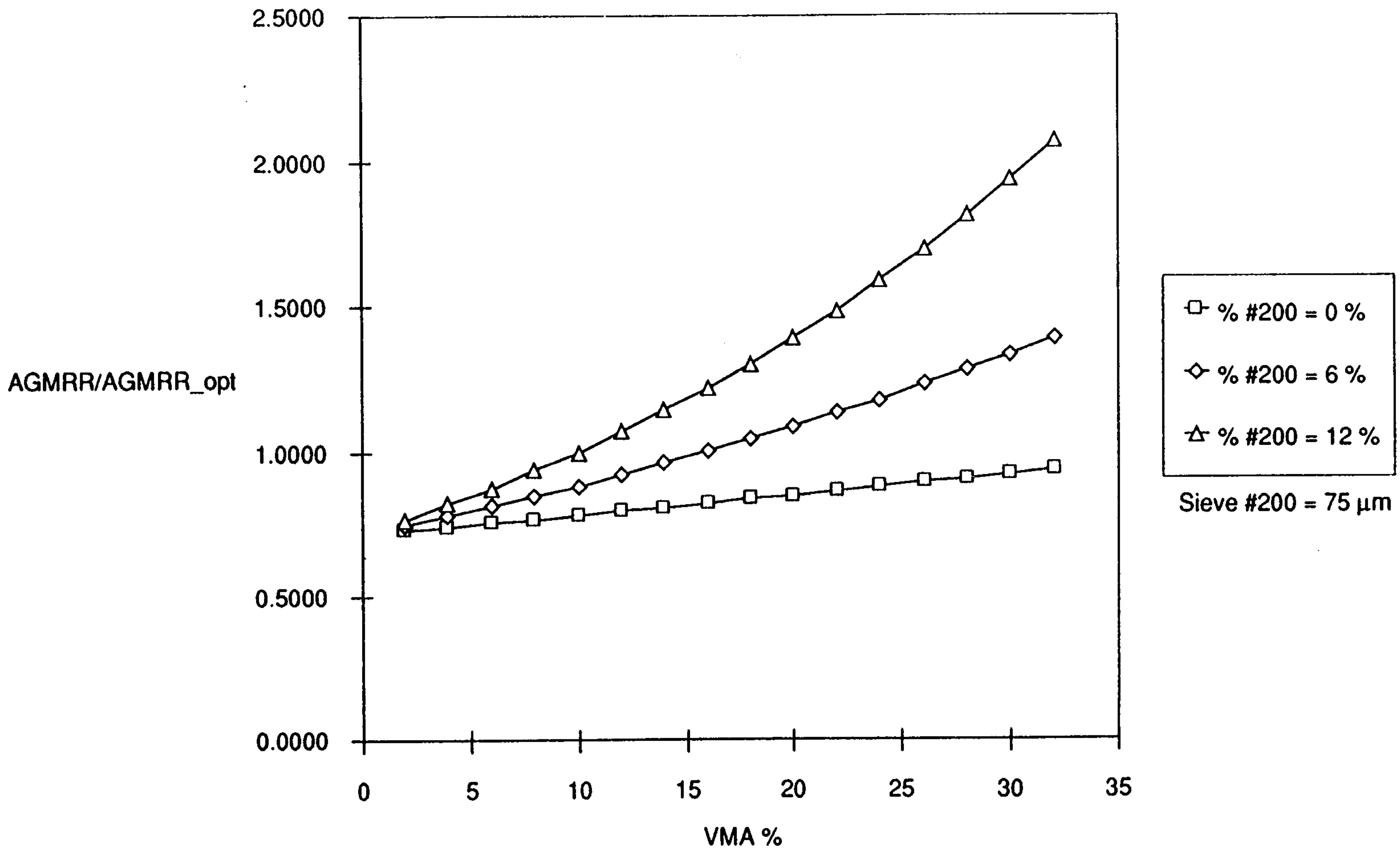


Figure 23. Effect of VMA and percent passing sieve #200 on the ratio of predicted to optimum aged resilient modulus.

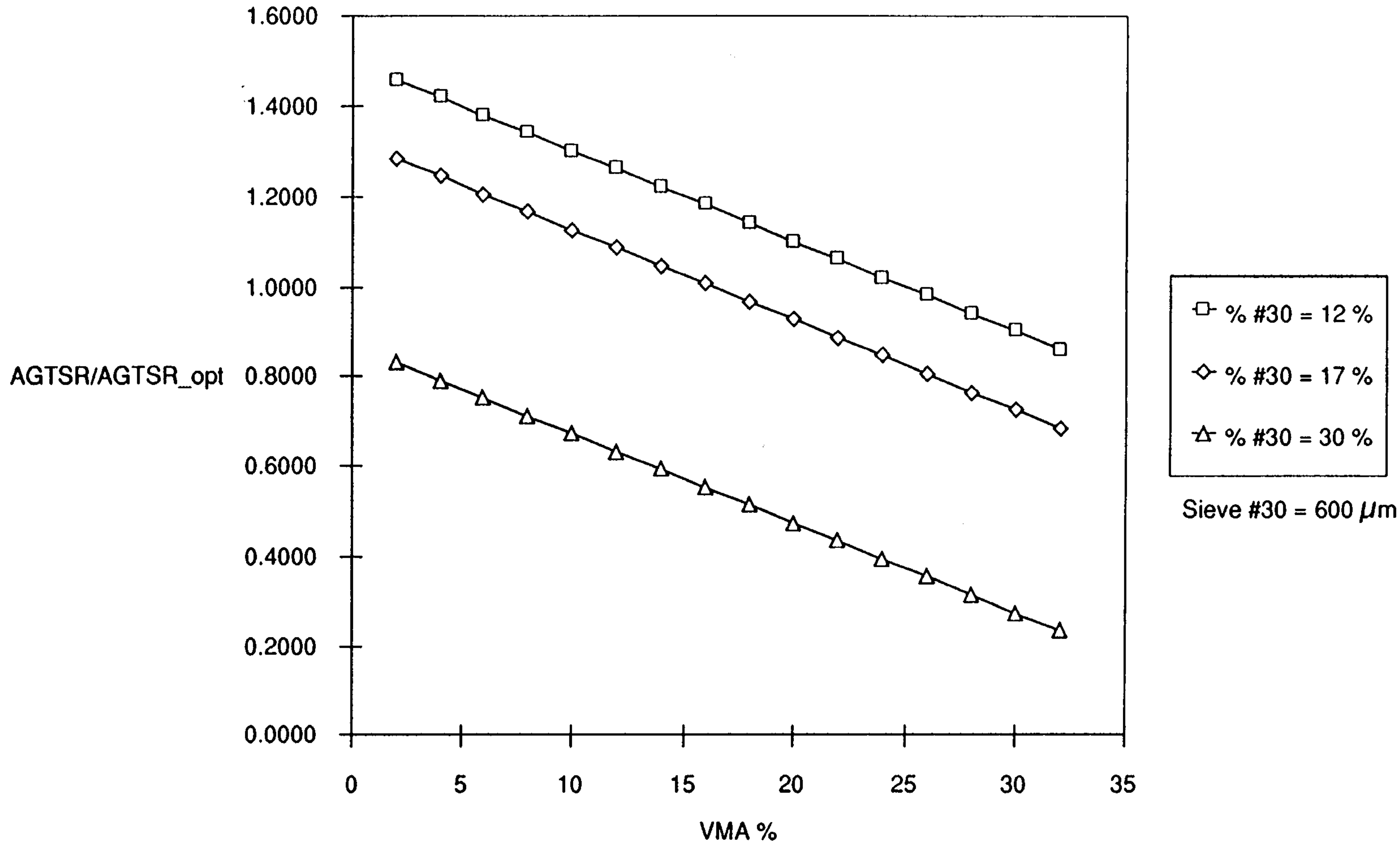


Figure 24. Effect of VMA and percent passing sieve #30 on the ratio of predicted to optimum aged indirect tensile strength.

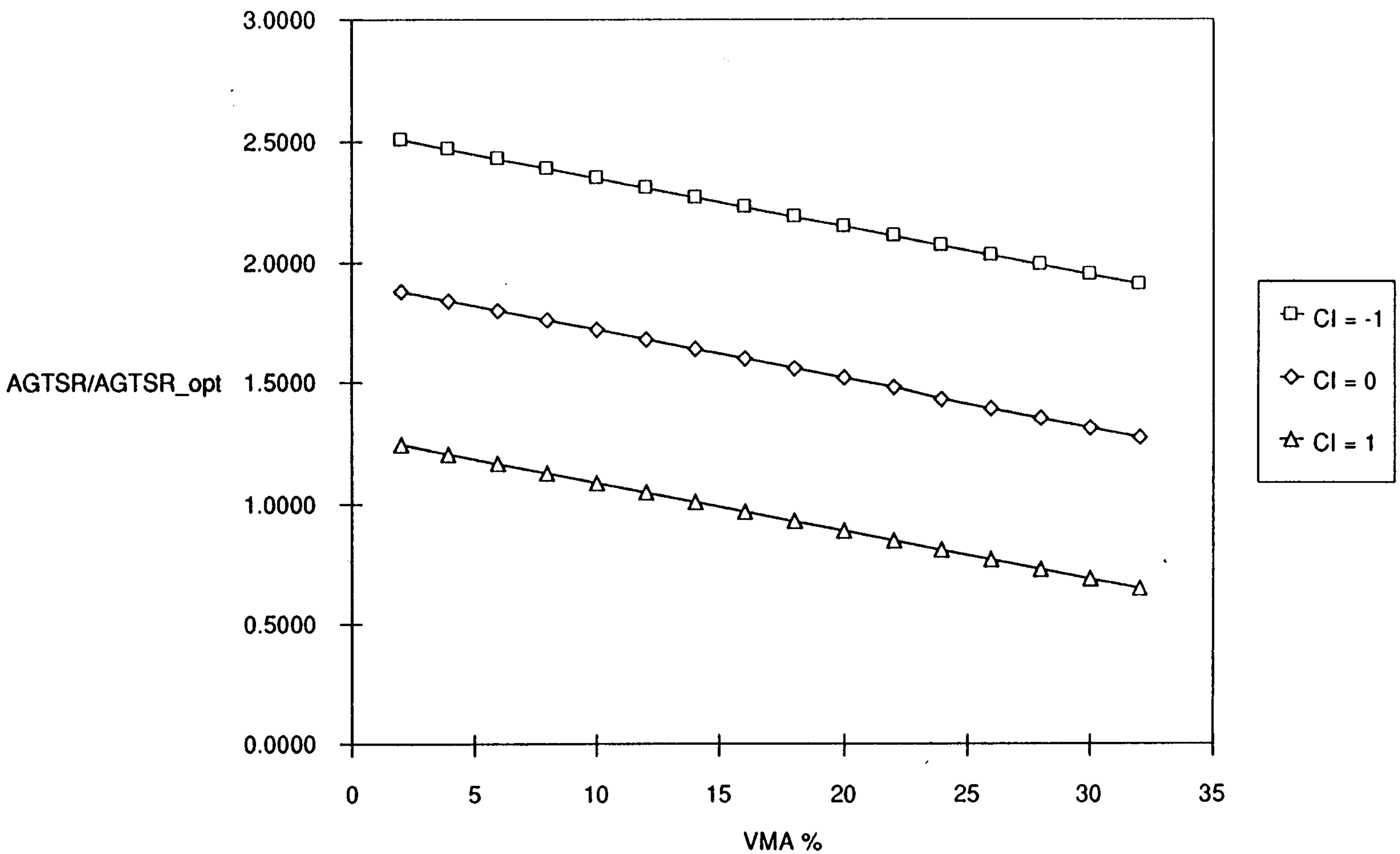


Figure 25. Effect of VMA and compaction index on the ratio of predicted to optimum aged indirect tensile strength.

Ratios of predicted to optimum tensile strength are calculated in table 13 for VMA values ranging from 2 to 32 in increments of 2. Equation (25) was used in the calculations. The first three columns represent the effect of the percent asphalt deviation, the three columns in the middle represent the effect of the compaction index (CI), and the last three columns represent the effect of the percent passing No. 200 (75 μm).

The results of the effect of VMA and percent asphalt deviation on the ratio of predicted to optimum indirect tensile strength presented in table 13 have been plotted in figure 18. A decrease in asphalt content results in smaller values of indirect tensile strength. This reduction is greater at low values of VMA (5 to 10 percent) than at high values (25 to 30 percent). However, the difference is not significant. An increase in asphalt content of 0.75 percent results in a slight increase on the indirect tensile strength. A more detailed study of equation (25) revealed that, for this study, the increase in tensile strength is true up to a 0.81 percent increase in asphalt content. Beyond this value, the tensile strength begins to decrease. The effect of VMA is a reduction in tensile strength as the percent VMA increases. A 2 percent increase in VMA produces an 8.3 percent decrease in tensile strength. This percentage (8.3 percent) is a function of the asphalt type and the percent passing sieve No. 200 (75 μm). For example, at 12 percent passing No. 200 (75 μm), the decrease in tensile strength corresponding to a 2 percent increase in VMA is 10.0 percent.

The effect of compaction index on the ratio of predicted to optimum indirect tensile strength is presented in figure 19. A decrease in compaction effort causes a decrease in the indirect tensile strength ratio. This decrease is more significant at low values of VMA (5 to 15 percent) than at high values (20 to 30 percent).

The effect of the percent passing sieve No. 200 (75 μm) is shown in figure 20. Below 25.7 percent VMA, the indirect tensile strength increases as the percent passing sieve No. 200 (75 μm) is increased. Above 25.7 percent VMA, the indirect tensile strength decreases as the percent passing sieve No. 200 (75 μm) is increased.

Ratios of predicted aged resilient modulus (AGMRR) to optimum aged resilient modulus ($AGRMM_{opt}$) are calculated in table 14 for VMA values ranging from 2 to 32 in increments of 2. Equation (27) was used for the calculations. The first three columns in this table represent the effect of the percent asphalt deviation, the middle three columns represent the effect of percent passing sieve No. 30 (600 μm), and the last three represent the effect of percent passing sieve No. 200 (75 μm).

The results in table 14 have been plotted in figure 21 for the percent asphalt deviation, in figure 22 for the percent passing sieve No. 30 (600 μm), and in figure 23 for the percent passing sieve No. 200 (75 μm).

The effect of the percent asphalt deviation is plotted in figure 21. A decrease in percent asphalt from optimum asphalt content produces an increase in aged resilient modulus. An increase in percent asphalt from optimum asphalt content produces a decrease in aged resilient modulus. The change due to asphalt percent deviation (±0.75 percent from optimum) increases as the percent VMA increases. For VMA values less than 12 percent, the change is less than 9 percent. For VMA values above 20 percent, the change is more than 15 percent.

Figure 22 shows a decreasing aged resilient modulus as the percent passing No. 30 (600 μm) decreases. This trend is more significant as VMA values increase. For VMA values below 10 percent, a decrease in percent passing No. 30 (600 μm) from 30 to 12 percent causes a decrease in aged resilient modulus of less than 9 percent.

The effect of the percent passing sieve No. 200 (75 μm) is plotted in figure 23. The aged resilient modulus increases as the percent passing sieve No. 200 (75 μm) increases. For a constant value of percent passing sieve No. 200 (75 μm), the aged resilient modulus increases as VMA increases. The change in aged resilient modulus due to a variation in percent passing sieve No. 200 (75 μm) increases as the percent VMA increases. For a 12-percent VMA, a change from 6 to 12 percent passing sieve No. 200 (75 μm) causes a 16-percent increase in aged resilient modulus, while for a 28-percent VMA a similar change in percent passing sieve No. 200 (75 μm) causes a 41-percent increase in aged resilient modulus.

Ratios of predicted aged indirect tensile strength (AGTSR) to optimum aged indirect tensile strength ($AGTSR_{opt}$) are calculated in table 15 for VMA values ranging from 2 to 32 in increments of 2. Equation (28) was used for the calculations. The first three columns in this table represent the effect of percent passing sieve No. 30 (600 μm). The last three columns represent the effect of the compaction index.

The results in table 15 have been plotted in figure 24 for the percent passing sieve No. 30 (600 μm) and in figure 25 for the compaction index.

Figure 24 shows a decrease in aged indirect tensile strength as the percent passing No. 30 (600 μm) increases. Figure 25 shows a decrease in aged indirect tensile strength as the VMA increases. All lines are parallel indicating that the change in aged tensile strength due to percent passing No. 30 (600 μm) or compaction index is the same at all levels of VMA.

CHAPTER 7. APPLICATION OF RESULTS TO PERFORMANCE-RELATED SPECIFICATIONS

INTRODUCTION

A 1976 publication reported that half of the states in the United States use statistical quality assurance techniques for acceptance of highway work, and another 25 percent have systems in various stages of development.[1] Many of these systems provide for reduced pay to contractors for work that does not meet specification requirements. Unfortunately, most of the payment adjustment plans are based on existing specifications that are not tied directly to pavement performance.

Although it is generally accepted that performance-related specifications are desirable, no generally accepted definition of a performance-related specification appears to be available. The primary purpose of a specification is to ensure that the constructed product provides acceptable performance. The reason for seeking performance-related specifications is to have enforceable limits that relate acceptability to an agreed-upon, objective measure of pavement performance.

An appropriate performance-related specification will include a statistical quality assurance program based on predicted pavement performance, will be enforced by a pay adjustment penalty for work that does not meet agency minimum limits, and will include a bonus for work exceeding some limit. Performance in the system will be defined by a numerical value, such as ESAL to some level of PSI, or repetitions to other measures of performance.

A suitable statistically-oriented end-result specification, with a quality assurance system and pay adjustment element, can be based on predictions of pavement performance determined from relationships between normal specification items, such as asphalt content, aggregate gradation, air void content and strength characteristics.

As reported in chapter 1 of this report, early progress in using statistically oriented end-result specifications was reviewed in NCHRP Synthesis of Highway Practice 38 in 1976.[1] More recently, other publications have introduced fundamental concepts of performance-related specifications and associated pay adjustment factors. (See references 13 and 32-38.) The research effort reported here is a continuation of research undertaken in a project of the National Cooperative Highway Research Program, NCHRP project 10-26A, and is part of a current FHWA program on performance-related specifications in highway construction.[13]

The purpose of this chapter is to outline an objective procedure for using the results of the study: (1) to define acceptability limits for asphalt concrete construction, and (2) to determine pay adjustment factors using results of mix design tests and tests on samples obtained from the plant and compacted pavement.

BASIC APPROACH

The general framework for developing a performance-related specification was introduced in chapter 2, figure 1. Figure 1 indicates that M&C variables generally are related to other variables that predict performance, through what are called secondary and primary relationships. Secondary relationships relate mixture composition properties (aggregate gradation, asphalt content, air voids, VMA, etc.) to mix structural properties (resilient modulus, tensile strength, fatigue life, etc.), which are themselves related to some measure of pavement performance. Measures of pavement performance might include load repetitions to specified levels of Present Serviceability Index (PSI), or repetitions to specified levels of fatigue cracking, rutting, or water damage.

The basic premise in the approach is that the ratio between performance predictions for actual conditions, N_a, and performance predictions for optimum design or target conditions, N_o, can be used to calculate pay factors. Performance must be defined by a numerical value, such as ESAL or repetitions to some measure of performance. It is important to note that only ratios are involved. As long as the same rules are followed in determining test properties and in predicting performance for actual and target conditions, the approach will not be highly sensitive to specific levels of predicted ESAL, but will be sensitive to the specific algorithm used.

DEVELOPMENT OF PREDICTION EQUATIONS

One of the objectives of this project was to determine relationships between M&C properties and performance-related mixture properties using laboratory data generated in the study. Relationships between dependent and independent variables were developed using linear multiple regression techniques with the Statistical Package for the Social Sciences (SPSS), as described in chapter 6 and appendix D.[39,40]

Final regression equations resulting from the analysis are summarized in chapter 6, table 11. Acceptance of a particular model was based on the r-square and standard error output from the SPSS statistical program. The models for compaction index (CI), resilient modulus (MR), tensile strength (TS) and repetitions to failure (N) in the diametral test in table 11 were accepted for further study and possible use in developing a procedure for quality assurance of asphalt concrete construction based on the materials and construction factors included in the study.

VALIDITY OF THE PREDICTION EQUATIONS

The degree to which the chosen models predict individual test results from which they were derived can be seen in table 16. While not as good perhaps as many researchers would like, in general individual results are predicted within a factor of two or less. As discussed in the following paragraphs, differences between predicted and actual test values represent testing and operator variability, as well as inadequacies in the regression models.

Table 17 includes calculations made using study equations from table 11 and data collected independently for NCHRP Project 10-26A. Because sufficient information was not available from project records at the time of the preparation of this report, it was necessary to assume values for

Table 16. Comparisons between performance predictions using derived equations for CI, MR, TS and N, and project test data.

CASE	%AC +/- OPT	#30 %	#200 %	VOIDS %	VMA %	AC TYP	AC PEN 77F	CI CALC	CI TEST	MR CALC W/TYP	MR CALC W/PEN	MR TEST	TS 77F	TS TEST	N (FAT)	N TEST
	INPUT							OUTPUT								
36	-0.75	18.1	2.1	14.4	24.0	1	51	-1.38	-1	77	77	80	33	49	2769	
4	0.75	13.0	7.1	9.2	18.1	1	51	-0.71	-1	173	173	87	61	48	10971	
23	-0.75	30.4	2.1	16.1	24.6	1	51	-0.96	-1	99	99	93	46	47	5818	
20	-0.75	13.0	7.1	11.1	19.2	1	51	-0.70	-1	162	162	99	51	45	7451	
37	0.75	30.4	2.1	11.0	25.9	1	51	-0.83	-1	105	105	104	63	61	11742	
33	-0.75	18.1	12.5	18.5	20.7	1	51	-1.74	-1	93	93	107	26	32	1601	
24	0.75	30.4	12.5	13.2	24.1	1	51	-1.20	-1	127	127	108	47	58	6196	
44	-0.75	13.0	2.1	9.9	22.4	1	51	-0.73	-1	123	123	115	51	48	7412	
40	-0.75	13.0	12.5	10.9	19.3	1	51	-0.58	-1	203	203	122	60	40	10670	
21	0.75	13.0	12.5	9.8	20.9	1	51	-1.06	-1	149	149	137	52	64	7539	
50	0.00	18.1	7.1	12.1	21.9	1	51	-1.04	-1	142	142	176	50	61	7140	8853
22	-0.75	13.0	2.1	9.1	16.1	1	51	-0.25	0	212	212	207	62	87	11483	
3	-0.75	13.0	12.5	8.7	15.6	1	51	0.03	0	325	325	232	93	48	27881	
8	0.75	30.4	2.1	6.3	20.5	1	51	0.07	1	230	230	235	107	252	37943	
17	-0.75	30.4	12.5	10.4	19.5	1	51	0.23	0	342	342	253	110	116	40909	
11	0.00	30.4	2.1	4.5	19.3	1	51	0.60	1	384	384	307	152	155	83991	72917
12	0.00	18.1	2.1	9.4	17.4	1	51	-0.34	0	226	226	396	73	114	16206	
2	-0.75	13.0	7.1	3.0	14.5	1	51	1.07	1	584	584	401	178	171	118781	13645
19	0.75	30.4	12.5	5.6	14.8	1	51	0.27	0	400	400	537	134	174	63304	
38	0.75	18.1	7.1	1.6	14.3	1	51	0.93	1	556	555	558	193	239	142469	
46	0.75	13.0	12.5	1.9	11.0	1	51	0.96	1	674	675	558	219	172	187350	
26	-0.75	18.1	7.1	7.7	14.8	1	51	0.33	1	360	359	589	103	102	35488	202055
52	0.00	30.4	7.1	3.0	12.3	1	51	1.16	1	777	776	814	220	240	190835	
51	-0.75	30.4	7.1	6.6	16.5	1	51	0.80	1	461	461	868	149	302	80361	
43	-0.75	18.1	12.5	5.3	9.8	1	51	1.10	1	736	736	982	200	184	153685	
						AVG =		-0.16	-0.08	309	309	327	101	116	61350	74368
9	-0.75	30.4	12.5	9.3	14.0	0	87	0.67	1	197	198	292	89	107	25069	
16	-0.75	13.0	12.5	3.8	11.1	0	87	1.19	1	294	295	214	129	102	57776	
27	0.00	18.1	12.5	10.0	14.4	0	87	-0.28	0	125	125	220	53	85	7937	128846
54	-0.75	13.0	7.1	7.6	14.3	0	87	0.21	0	131	131	137	56	54	9116	
53	0.00	18.1	2.1	5.4	13.8	0	87	0.54	1	177	177	244	76	103	17970	
1	0.75	13.0	2.1	3.8	12.6	0	87	0.69	1	178	177	118	83	71	21835	
25	0.00	18.1	2.1	3.1	13.1	0	87	0.97	1	239	239	310	103	131	35211	
10	0.75	13.0	12.5	9.2	20.4	0	87	-0.92	-1	64	64	32	34	33	3016	
7	0.75	30.4	2.1	14.7	28.5	0	87	-1.45	-1	25	25	18	25	35	1570	
18	0.75	13.0	7.1	9.5	20.9	0	87	-0.91	-1	54	54	313	33	37	2767	
49	0.75	18.1	2.1	9.7	23.2	0	87	-0.85	-1	45	45	46	35	33	3145	
30	-0.75	30.4	12.5	16.8	20.8	0	87	-0.67	-1	72	72	74	34	23	3000	
45	-0.75	13.0	2.1	10.5	18.7	0	87	-0.65	-1	58	58	41	30	24	2195	
29	-0.75	13.0	2.1	11.2	19.2	0	87	-0.81	-1	51	51	29	27	17	1738	
41	0.00	13.0	12.5	9.3	16.6	0	87	-0.44	-1	108	108	47	48	25	6294	
14	-0.75	18.1	12.5	14.7	23.3	0	87	-1.22	-1	48	48	38	23	16	1243	
15	-0.75	30.4	12.5	3.0	12.4	0	87	1.57	-1	366	366	21	172	16	109303	
47	-0.75	13.0	2.1	4.5	16.2	0	87	0.62	1	144	144	168	71	92	15424	
39	-0.75	30.4	2.1	7.2	19.5	0	87	0.47	1	116	116	100	70	96	14677	
28	-0.75	13.0	12.5	6.1	14.2	0	87	0.59	1	187	188	245	84	126	22292	
34	0.75	30.4	2.1	2.2	18.6	0	87	0.70	1	144	144	139	97	121	30968	
6	0.75	13.0	2.1	2.4	18.2	0	87	0.67	1	143	143	117	94	116	28671	
32	-0.75	30.4	2.1	9.6	21.8	0	87	0.04	0	81	81	93	54	70	8178	
35	0.75	13.0	12.5	8.7	18.0	0	87	-0.70	-1	78	78	39	40	30	4222	
42	0.00	18.1	2.1	7.4	18.6	0	87	-0.05	0	101	101	116	55	63	8833	
48	-0.75	30.4	2.1	6.3	16.2	0	87	0.76	1	158	158	262	79	124	19621	
31	0.00	30.4	12.6	7.3	16.7	0	87	0.37	0	181	181	173	87	110	23825	
						AVG =		0.04	0.00	132	132	135	66	69	12999	128846

Table 17. Performance predictions using test data from NCHRP Project 10-26A.

INPUT CASE	%AC +/- OPT	#30 %	#200 %	VOIDS %	VMA %	AC TYPE	AC %	NO. BLOWS	OUTPUT CI	MR,77F PRED KSI	MR,77F TEST KSI	TS,77F PRED PSI	TS,77F TEST PSI	REPETITIONS,N PRED	REPETITIONS,N TEST
193	0.0	18.0	5.4	2.7	13.8	1	5.8	75	1.01	654	247	194	169	143362	93590
4	0.0	18.0	5.4	3.0	14.0	1	5.8	75	0.94	622	475	186	261	130226	52930
196	0.0	18.0	5.4	3.2	14.2	1	5.8	75	0.90	599	520	180	169	121709	19070
2	0.0	18.0	5.4	3.2	14.2	1	5.8	75	0.90	602	453	180	261	122082	39550
199	0.0	18.0	5.4	3.7	14.7	1	5.8	75	0.79	551	368	167	178	103643	8010
7	0.0	18.0	5.4	3.8	14.7	1	5.8	75	0.77	543	462	165	222	100427	7590
204	0.0	18.0	5.4	4.1	15.0	1	5.8	75	0.70	515	454	158	178	91086	29630
AVG =	0.0	18.0	5.4	3.4	14.4		5.8	75	0.86	584	426	176	205	116076	35767
N =	7	7	7	7	7		7	7	7	7	7	7	7	7	7
STD DEV =				0.49473	0.44673			0	0.11	48.9	90.78	12.61	42.05	18423.3	30368
101	0.0	18.0	5.4	7.5	18.0	1	5.8	28	-0.04	290	343	96	117	30340	6310
98	0.0	18.0	5.4	7.7	18.2	1	5.8	28	-0.09	280	336	94	117	28399	55170
106	0.0	18.0	5.4	8.1	18.2	1	5.8	28	-0.16	268	292	89	124	25343	25790
108	0.0	18.0	5.4	8.3	18.7	1	5.8	28	-0.22	253	238	86	124	23397	11240
AVG =	0.0	18.0	5.4	7.9	18.3		5.8	28	-0.13	273	302	91	121	26870	24628
N =	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
STD DEV =				0.36515	0.31254			0	0.08	16	48.42	4.74	4.041	3096.73	21977
78	-0.8	18.0	5.4	4.9	13.9	1	5.0	75	0.85	488	354	141	221	70562	12260
81	-0.8	18.0	5.4	5.2	14.1	1	5.0	75	0.78	464	504	135	178	63992	54090
75	-0.8	18.0	5.4	5.5	14.3	1	5.0	75	0.72	443	422	129	178	58303	4650
AVG =	-0.8	18.0	5.4	5.2	14.1		5.0	75	0.78	465	427	135	192	64286	23667
N =	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
STD DEV =				0.24495	0.18839			0	0.05	18.39	61.33	4.729	20.27	5009.13	21736
24	-0.8	18.0	5.4	9.9	18.3	1	5.0	28	-0.24	210	428	68	168	14019	54580
14	-0.8	18.0	5.4	9.9	18.3	1	5.0	28	-0.25	209	398	68	147	13976	20450
20	-0.8	18.0	5.4	10.3	18.7	1	5.0	28	-0.33	195	349	64	168	12281	6220
17	-0.8	18.0	5.4	10.4	18.7	1	5.0	28	-0.35	193	311	63	147	11918	16540
AVG =	-0.8	18.0	5.4	10.1	18.5		5.0	28	-0.30	202	372	66	158	13049	24448
N =	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
STD DEV =				0.26300	0.23581			0	0.06	8.979	51.84	2.519	12.12	1105.98	20966
47	0.0	18.0	7.5	1.8	13.4	1	5.8	75	1.18	769	363	230	176	210257	13100
39	0.0	18.0	7.5	1.8	13.8	1	5.8	75	1.16	749	374	228	211	205652	104190
41	0.0	18.0	7.5	2.0	13.6	1	5.8	75	1.14	742	538	223	176	196361	162350
38	0.0	18.0	7.5	2.3	13.8	1	5.8	75	1.07	708	345	214	176	178369	27290
AVG =	0.0	18.0	7.5	2.0	13.7		5.8	75	1.14	742	405	224	185	197660	76733
N =	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
STD DEV =				0.23629	0.19984			0	0.05	25.1	89.47	7.261	17.5	14099.1	69709
68	0.0	18.0	7.5	5.6	16.8	1	5.8	28	0.35	409	384	131	140	59709	15540
71	0.0	18.0	7.5	5.6	16.7	1	5.8	28	0.35	410	467	131	148	59819	94980
62	0.0	18.0	7.5	5.8	16.9	1	5.8	28	0.31	396	401	127	140	55990	5240
65	0.0	18.0	7.5	5.9	17.0	1	5.8	28	0.29	390	392	125	165	54218	29190
AVG =	0.0	18.0	7.5	5.7	16.8		5.8	28	0.33	401	411	128	148	57434	36238
N =	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
STD DEV =				0.15000	0.11527			0	0.03	9.541	37.97	2.808	11.79	2786.46	40372
28	-0.8	18.0	7.5	4.1	13.5	1	5.0	75	1.04	582	586	170	234	107099	55420
33	-0.8	18.0	7.5	4.2	13.6	1	5.0	75	1.02	572	559	167	234	103514	15130
36	-0.8	18.0	7.5	4.3	13.7	1	5.0	75	1.00	562	385	165	234	100048	15530
31	-0.8	18.0	7.5	4.5	13.9	1	5.0	75	0.96	545	619	160	234	93811	6720
AVG =	-0.8	18.0	7.5	4.3	13.7		5.0	75	1.01	565	537	166	234	101118	23200
N =	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
STD DEV =				0.17078	0.15031			0	0.04	15.94	104.4	4.187	0	5658.31	21861
182	-0.8	18.0	7.5	8.3	17.3	1	5.0	28	0.12	288	553	91	144	26502	28190
192	-0.8	18.0	7.5	8.4	17.5	1	5.0	28	0.10	283	349	89	144	25567	8630
184	-0.8	18.0	7.5	8.4	17.5	1	5.0	28	0.10	283	371	89	144	25567	5480
AVG =	-0.8	18.0	7.5	8.4	17.4		5.0	28	0.10	284	424	90	144	25878	14100
N =	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
STD DEV =				0.05774	0.08126			0	0.01	3.274	112	0.839	0	539.697	12304

asphalt type, percent passing the No. 30 (600 μm) sieve, and specific gravity of the aggregate.

The NCHRP 10-26A study included specimens compacted with the Marshall apparatus using 75 and 28 blows. The CI equations predict values of close to 1 and 0, respectively, for these two levels of compaction. In comparison, CI values of 1 and 0 represented high and medium compactive effort using a kneading compactor in this study, from which the equation for CI was developed.

Differences between calculated and measured test values for resilient modulus, tensile strength and repetitions are somewhat variable, and represent both laboratory and operator differences, as well as differences in testing conditions. The larger standard deviations for the test results compared to predicted values reflect these sources of error. Differences between predicted and measured values are larger for some combinations of M&C variables than for others, and represent inadequacies in the models.

Comparisons between calculated and actual test values in tables 16 and 17 indicate that, in general, the computed and observed values are within the same order of magnitude, and frequently vary by a factor of less than 5. However, this indicates that the equations should not be used to calculate absolute values for single test results, as will be discussed further in subsequent paragraphs.

It was necessary to make assumptions for some of the input data from NCHRP Project 10-26A, but the assumptions were applied consistently, and, as explained in the previous section, would not significantly affect the ratio Na/No which is the basis for the procedure. Actual values calculated for MR, TS and N depend both on assumptions made and on the validity of the equations themselves. Assumptions that are particularly significant in determining the magnitude of calculated values of MR, TS and N are asphalt type and compaction index.

In addition, other variables, particularly asphalt content, percent air voids and aggregate gradation, may produce effects that, in extreme cases, will not be technically acceptable to some people. A major indication in this respect is that low asphalt content, high air void mixes display high resilient modulus values, which in turn will predict high values of N. High void, low asphalt content mixes, in fact, may have high modulus values; however, such mixes are not generally acceptable because of their tendency to ravel and to display poor resistance to stripping.

It is also known that large amounts of filler, No. 200 (75 μm) material, will increase the modulus of an asphalt concrete mix, and this, also, is reflected in the equations derived in this study. Most materials engineers do not find these mixes acceptable, since excess filler can cause bleeding, rutting, or ravelling, depending on other characteristics.

All M&C variables that affect mix characteristics are interdependent, and it is difficult to develop models, or equations, that reflect all possible effects. For example, the test data produced in this study show that percentages of aggregate passing the No. 30 (600 μm) and No. 200 (75 μm) sieves affect compaction. Unfortunately, the data are not extensive enough to model this effect completely, and other means for handling the situation are required.

Because of the limitations cited above, it may be necessary to include restrictions on the use of equations derived from the test data.

Table 18 includes calculations from other studies for which reasonable information was available to compute the required values. Results are variable, reflecting, to some unknown extent, the need to estimate some of the M&C variables involved. For example, the data for the Asphalt-Aggregate Mixture Analysis System (AAMAS) project were assembled from mix design data, field core data and specimens compacted from loose field samples. [41,42]

The data from reference 43 in table 18 were from a study of the effects of asphalt grade on tensile strength, using a trap rock and a gravel aggregate. Since asphalt penetration was given, these forms of the MR and TS equations were used to predict MR and TS. Gyratory compaction was used to achieve the required air voids, and this is reflected in the computed CI values. Although means are reasonably close, the equations indicate a greater effect of asphalt grade than exhibited by the test data.

The data from reference 44 represent averages of a large number of field cores. The most interesting aspect of these comparisons is how the CI values reflect the results of traffic compaction.

The data from reference 45 in table 18 compares test results from field cores, after a few years under traffic, with laboratory mix design data. The problem being investigated was rutting that occurred within a year or so of construction. Rutting was more severe in the surface course than in the binder course. One can speculate that the higher CI values calculated for the cores reflect the effect of additional compaction under traffic, and possibly the influence of low compaction, both in the laboratory and in the field.

It is evident from the above illustrations, that it probably will not be possible to use the equations to calculate absolute values for single samples of an asphalt concrete mix. The equations reflect both the variability of the original test data, and any unexplained effects that may have been introduced in the development and use of the equations. Successful implementation, therefore, will depend on uniform testing to obtain the appropriate M&C test values, the use of multiple tests to reduce the effects of testing variability, and retesting where significant pay penalties are indicated.

QUALITY ASSURANCE PLAN

The general framework for developing a performance-related specification was introduced in figures 1 and 2. The specific elements that are incorporated into the plan outlined below are shown in figure 26, from reference 13. Secondary relationships are included in the boxes marked "MATERIALS CHARACTERIZATION" and "M&C VARIABLES" in figure 26. Primary relationships are included in the boxes marked "DESIGN ALGORITHM."

Table 18. Performance predictions using test data from different sources.

CASE	%AC +/- OPT	#30 %	#200 %	VOIDS %	VMA %	AC TYP	AC %	AC PEN 77F	CI CALC	MR PRED KSI	MR TEST KSI	TS PRED PSI	TS TEST PSI	TS TEST PSI	N CALC *
	INPUT								OUTPUT						
TEST DATA FROM REFERENCE 42															
CO-0009															
CO JMF	0.0	17.5	4.9	5.5	15.8	1	5.5		0.41	411		128			56515
CO FIELD	-0.5	20.0	6.0	8.2	17.1	1	5.0		0.10	308	519	96			29990
MI-0021															
MI JMF	0.0	24.9	5.5	5.1	18.6	1	5.5		0.47	397		142			72177
MI FIELD	-0.1	26.0	4.0	3.7	16.4	1	5.4		0.83	516	546	171			108600
TX-0021															
TX JMF	0.0	23.0	2.7	6.8	15.3	1	5.5		0.33	380		114			44407
TX FIELD	0.1	30.8	6.8	8.8	17.1	1	5.6		0.13	344	677	111			41684
VA-0621															
VA JMF	0.0	17.0	5.5	8.7	19.5	1	4.5		-0.35	227		79			19456
VA FIELD	0.1	19.4	5.6	5.9	17.2	1	4.6		0.28	369	620	123			51776
WY-0080															
WY JMF	0.0	17.6	5.5	4.7	13.0	1	6.0		0.70	548		152			83435
WY FIELD	-1.3	17.6	5.5	5.8	19.9	1	4.7		0.52	246	661	98			31721
REFERENCE 43, PAGE 26 - TESTS ON TWO DIFFERENT AGGREGATES															
													ROCK	GRAVEL	
AC20	0.0	25.5	5.0	6.0	15.89		5.5	68	0.48	275		106	69	103	37629
	0.0	25.5	5.0	6.0	14.22		4.8	68	0.57	307		110	70	108	40352
	0.0	25.5	5.0	8.0	17.68		5.5	68	0.09	202		83	62	93	21490
	0.0	25.5	5.0	8.0	16.05		4.8	68	0.18	225		85	62	101	23007
AC10	0.0	25.5	5.0	6.0	15.89		5.5	110	0.48	91		58	58	71	9950
	0.0	25.5	5.0	6.0	14.22		4.8	110	0.57	102		60	59	78	10670
	0.0	25.5	5.0	8.0	17.68		5.5	110	0.09	67		45	62	71	5682
	0.0	25.5	5.0	8.0	16.05		4.8	110	0.18	75		47	57	91	6083
AC5	0.0	25.5	5.0	6.0	15.89		5.5	187	0.48	12		20	39	63	868
	0.0	25.5	5.0	6.0	14.22		4.8	187	0.57	14		20	37	62	931
	0.0	25.5	5.0	8.0	17.68		5.5	187	0.09	9		15	37	52	496
	0.0	25.5	5.0	8.0	16.05		4.8	187	0.18	10		16	38	65	531
											AVG	55	54	80	
REFERENCE 44, PAGE 519 - SURVEY OF PERFORMANCE									- TESTS ON PAVEMENT CORES						
LOW TRAF	0.0	18.0	5.0	1.9	14.40	0	5.5		1.11	264	332	126			54830
HIGH TRAF	-0.3	18.0	5.0	1.3	13.40	0	5.2		1.35	308	408	140			69120
REFERENCE 45 - RUTTING PROBLEMS, I-55 - 50 BLOW MARSHALL COMPACTION															
SURFACE COURSE															
LAB	0.0	27.0	10.2	4.2	16.20		5.3	79	0.75	273		123			52091
CORES	0.1	27.0	10.2	2.6	14.40		5.4	79	1.02	340		150			80680
BINDER COURSE															
LAB	0.0	19.0	6.7	4.0	13.50		4.3	79	0.81	284		115			45089
CORES	0.5	19.0	6.7	2.4	12.70		4.8	54	0.96	585		186			131009

* No comparisons with N_{TEST} are included because traffic data were not available.

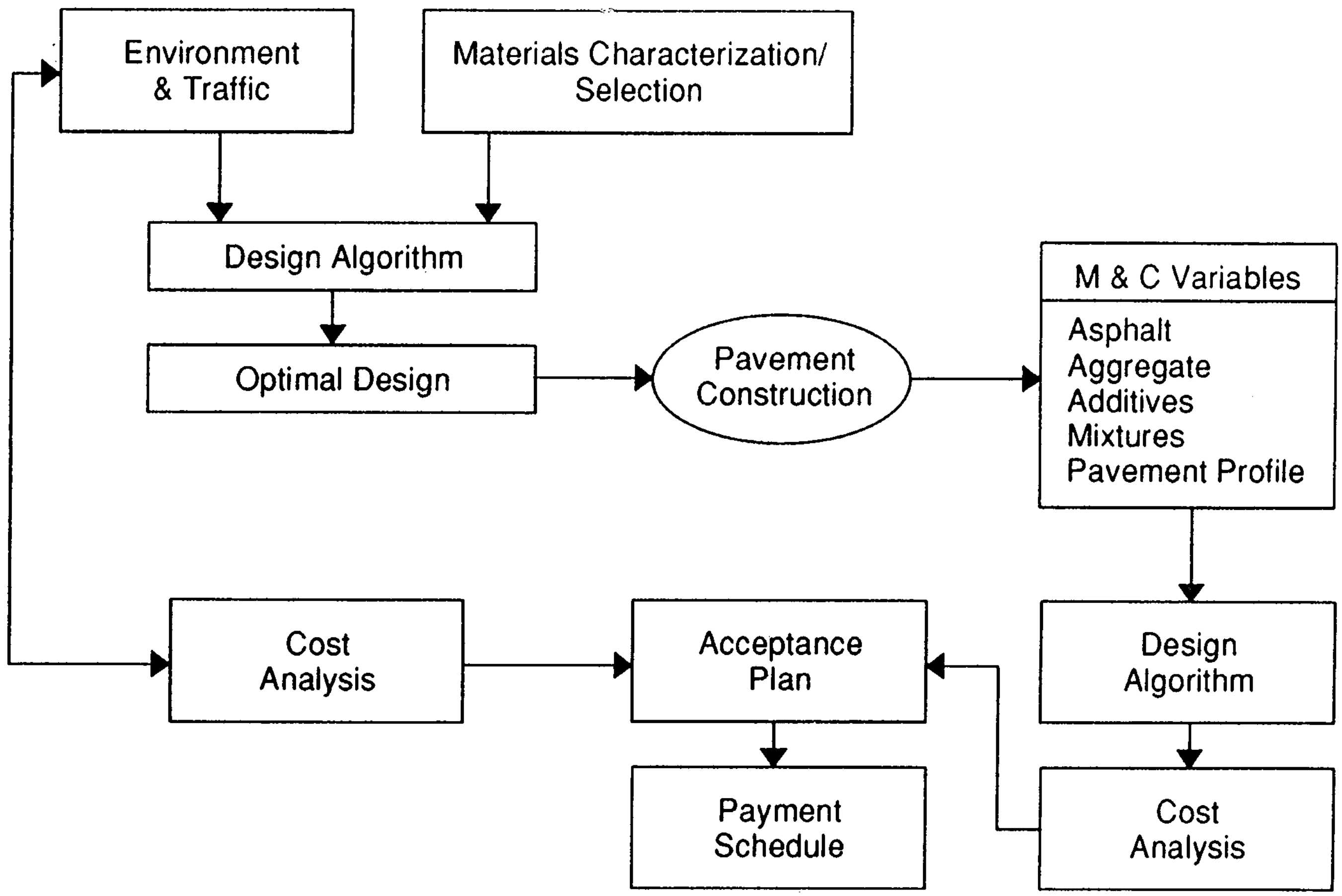


Figure 26. Generalized framework for a performance-related specification for hot-mix asphaltic concrete.[13]

The basic premise of the approach is that performance predicted for actual conditions will be compared to performance predicted for optimum design, or other conditions for which the contracting agency is willing to pay 100 percent of the bid price. The ratio of these two predictions is used to calculate pay factors.

Implementation of the procedure discussed involves the steps below, which follow closely the process outlined in figure 26:

- Select environment and traffic input data that are consistent with the design algorithm.
- Select materials and perform mix design tests to determine materials and mix characteristics consistent with the method being used.
- Use the prediction equations for CI and MR or TS and N and a design algorithm to estimate pavement life for optimum mix characteristics. This will provide a basis for selecting a "target" pavement life, to which the predicted life of the constructed pavement will be compared.
- Sample and test the constructed mix and determine the required mix characteristics (M&C variables).
- Use the prediction equations for CI and MR or TS and N and a design algorithm to estimate pavement life using the M&C characteristics for actual, as-constructed conditions. This will provide a predicted pavement ("actual") life value which will be compared to the "target" predicted life.
- Apply the algorithm for determining acceptance and calculating pay factors.

DESIGN ALGORITHMS

As indicated above, calculated values of M&C variables will be used with design algorithms, i.e., primary prediction models, to predict pavement life. Several approaches were considered in this study, including:

- Use of equations for tensile strength, TS, and fatigue life, N, developed in chapter 6 to predict performance for "actual" and "target" M&C variable levels. A similar approach also might include reductions in fatigue repetitions from water damage.
- Use of the AASHTO GUIDE to determine repetitions (W18 or ESAL) to various levels of PSI. The equations developed in chapter 6 would be used to modify the layer coefficients for asphalt concrete in the equation $SN = a_1(D_1) + a_2(D_2) \ldots$.etc.[14]
- Use of structural analysis models developed from elastic theory, such as those listed in chapter 3, to calculate stress or strain, and repetitions to failure.

- Use of simplified equations to calculate stress or strain, such as those developed at Illinois for the ILLI-PAVE program.[46]

- Use of life cycle cost models to determine pay factors.[1,32]

- Use of the concept of statistical quality level to determine pay factors.[32,33]

PRIMARY PREDICTION METHODS

The first two methods above, using the equations developed in this study, with and without the AASHTO Guide equations, were selected as the primary methods for further development. Methods in which stress or strain is calculated directly from elastic theory were not developed, in order to keep the system somewhat simple to use. However, the simplified algorithms based on ILLI-PAVE were investigated for possible use. Table 19 illustrates how the three methods compare.

It is clear from table 19 that the three methods used to estimate repetitions to failure from M&C variables will not predict the same levels of repetitions. The number of repetitions estimated using the AASHTO equations was based on a terminal PSI of 2.5, but could have been increased by assuming a lower terminal PSI. The study equations could have been made to produce a larger number of repetitions by reducing the value of the stress factor in the equation for N. However, the relative effects used in the proposed method would not change.

The comparisons of relative repetitions, N Ratio (shown in table 19), indicate that the ILLI-PAVE and AASHTO Guide models, which depended on calculated MR values, will predict similar ratios. Ratios derived from the study equations, which use TS to calculate repetitions, however, differ substantially from the other two.

Because the ratios derived using the ILLI-PAVE algorithms were similar to those produced by the AASHTO Guide, because ILLI-PAVE is restricted to a full-depth asphalt pavement, and because the AASHTO Guide is accepted by many design organizations, no further work was done to develop the ILLI-PAVE model.

Additional work was done, however, to develop further the use of the study equations to predict performance for "actual" and "target" M&C variable levels. This approach used equations for CI and TS to estimate N. In this case, failure is an arbitrary number, as defined by fatigue failure in the indirect tensile test procedure used in the study. It is calculated using the relationship between tensile strength and fatigue failure repetitions derived from the test data.

Unfortunately, when used with actual test data from projects, the lack of a method for taking thickness into account, and some rather wide differences in repetition ratios, led to the abandonment of the study equations in favor of the AASHTO Guide algorithms for the development of a system for possible use in a performance-related specification, with quality assurance and pay adjustment factors.

Table 19. Comparison of primary prediction models.

CASE FROM TABLE 16	INPUT AC THICK in.	INPUT AC MR ksi	INPUT SUBGR MOD ksi	ILLIPAVE AC STRAIN (1)	ILLIPAVE PRED N	ILLIPAVE N RATIO	AASHTO GUIDE PRED N	AASHTO GUIDE N RATIO	EQUATIONS PRED N	EQUATIONS N RATIO
43	6	736	7.500	161	1,207,675	1.0	288,000	1.0	153,685	1.0
38	6	556	7.500	200	629,685	0.5	173,000	0.6	142,469	0.9
11	6	384	7.500	266	266,610	0.2	60,100	0.2	83,991	0.5
22	6	212	7.500	421	67,114	0.1	9,840	0.0	11,483	0.1
43	8	736	7.500	102	4,759,190	1.0	1,640,000	1.0		
38	8	556	7.500	126	2,481,455	0.5	978,000	0.6		
11	8	384	7.500	168	1,050,654	0.2	337,000	0.2		
22	8	212	7.500	266	264,481	0.1	45,900	0.0		
43	10	736	7.500	71	13,788,058	1.0	6,810,000	1.0		
38	10	556	7.500	89	7,189,133	0.5	3,910,000	0.6		
11	10	384	7.500	118	3,043,897	0.2	1,300,000	0.2		
22	10	212	7.500	187	766,240	0.1	174,000	0.0		

(1) UNIT STRAIN, E-6 in./in.

1 in = 25.4 mm
1 ksi = 6.89 MPa

The AASHTO GUIDE is used in this method to determine repetitions (W18 or ESAL) to various levels of PSI for different levels of M&C variables. An algorithm was developed to modify the layer coefficients for asphalt concrete in the equation $SN = a_1(D_1) + a_2(D_2)$....etc. by MR estimated from M&C variables using the study equations for CI and MR.

Calculated values of MR are converted to coefficients using the following algorithm:

$$\text{Coefficient} = 0.0842514 + 0.582986(M) - 0.228945(M)^2 \tag{33}$$

$$\text{where } M = \frac{\text{resilient modulus for actual M\&C values}}{\text{resilient modulus for target M\&C values}}$$

The algorithm was derived from figure 2.5 in the AASHTO Guide for Design of Pavement Structures, a chart for estimating structural layer coefficient of dense-graded asphalt concrete based on the elastic (resilient) modulus.[25] The algorithm always produces a coefficient of 0.44 for design conditions (ratio = 1.0), but may be modified where desired.

The use of the AASHTO Guide has been illustrated by calculating ESAL for the average mix characteristics given in table 17 for the NCHRP 10-26A project data. The first set of data considered the design set of M&C values, for which the ESAL was given a life of 20 years. The corresponding years were then calculated for each of the other sets of M&C conditions and plotted graphically, as shown in figure 27. Figure 27 shows how the various mixture M&C variables affect predicted performance. The first group of bars reflects the data obtained with the 28 blow compaction procedure; the second set reflects the group compacted with 75 blows. The effect of compaction is quite clear. Other factors are not quite as clear, reflecting the interaction effect of these variables in the equation used to estimate MR.

EXAMPLE SPREADSHEET AND TYPICAL PROJECT DATA

A computation form using a spreadsheet with a personal computer was developed for use in implementing the concepts outlined above. The spreadsheet is shown in tables 20 and 21, along with actual data from two projects provided by the Materials & Research Division of the Maryland State Highway Administration. Mix design data are shown in the Design column of tables 20 and 21. The test data shown in the other columns were obtained from plant extraction tests and from density tests on pavement cores.

The mixes in the examples were actually used on two different Interstate highway projects; however, the pavement designs, and the application to determining pavement acceptance, are not real and are supplied for illustrative purposes only.

The first five lines of the spreadsheet provide for project and lot identification. To be effective a minimum of three and preferably five or more samples should be taken from each lot. Field test samples should be taken using a random sampling plan. It is particularly important that any testing done to establish design or target M&C properties be consistent with

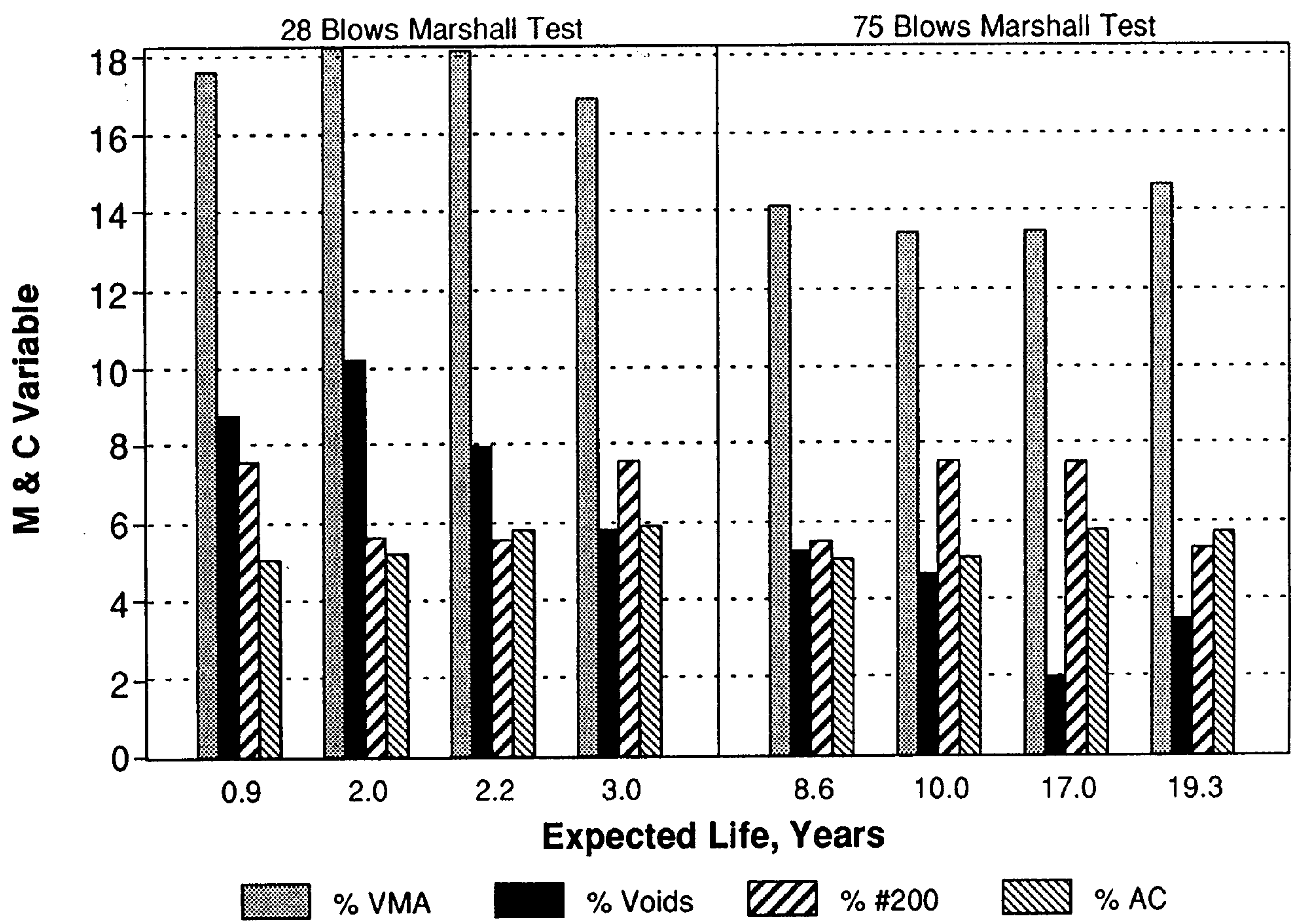


Figure 27. Effect of M&C variables on pavement life.

Table 20. Pay factors for quality assurance of asphalt concrete - example 1.

LINE NO.	M&C ITEMS	DESIGN VALUES	TEST DATA & SAMPLE NUMBER NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7	NO.8	TEST SAMPLE AVERAGE
1	PROJECT ______________										
2	DATE __/__/__ TIME __/__ AM/PM										
3	SAMPLE/CORE NO(S). __________										
4	LOCATION ____________										
5											
6	PAVEMENT DESIGN FACTORS (AASHTO GUIDE)										
7	* ESAL/YEAR (THOUSANDS)	326.7	326.7	326.7	326.7	326.7	326.7	326.7	326.7	326.7	326.7
8	* INITIAL PSI	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
9	* FINAL PSI	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
10	* Z(R)	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
11	* S(O)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
12	* SUBGRADE MODULUS,PSI	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500
13	* D1 (ASPH CONC), IN.	1.50	1.53	1.63	1.67	1.55	1.55	1.65	1.53	1.56	1.58
14	** A1	0.44	0.37	0.39	0.36	0.39	0.38	0.37	0.35	0.37	0.37
15	* D2 (ASPH CONC), IN.	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
16	** A1	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
17	* D3 (AGG BASE), IN.	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
18	** A3	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
19	* D4 (AGG BASE), IN.										
20	** A3										
21	* SN	4.02	3.92	4.00	3.97	3.96	3.95	3.97	3.90	3.94	3.95
22											
23	MATERIALS CHARACTERISTICS - ASPHALT CONCRETE										
24	* LAYER ____________										
25	* ASPHALT (TYPE/PEN 77F)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.00
26	* ASPHALT CONTENT (%)	4.4	4.4	4.3	4.1	4.2	4.2	4.2	4.7	4.4	4.31
27	** UL										
28	** LL										
29	* AGGREGATE (TYPE ?)										
30	** MAX SIZE, IN.	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
31	* AGG % <#4 SIEVE (JMF)										
32	** UL (JMF)										
33	** LL (JMF)										
34	* AGG % <#30 SIEVE (JMF)	21.0	23.7	24.0	22.0	22.5	23.5	22.0	22.5	22.5	22.83
35	** UL (JMF)										
36	** LL (JMF)										
37	* AGG % <#200 SIEVE(JMF)	4.3	3.7	4.4	3.6	3.6	4.1	3.9	4.0	3.7	3.86
38	** UL (JMF)										
39	** LL (JMF)										
40	* AIR VOIDS (%)	4.0	7.4	6.7	7.7	6.9	7.2	7.4	6.8	7.1	7.15
41	** UL (FIELD)										
42	** LL (FIELD)										
43	* VMA (%)	14.9	17.6	16.7	17.3	16.7	17.0	17.1	18.0	17.3	17.21
44	** UL (DESIGN)										
45	* ** LL (DESIGN)										
46	* COMPACTION INDEX	0.75	0.26	0.40	0.26	0.39	0.34	0.29	0.19	0.27	0.30
47	* RES MODULUS (MR,KPSI)	522.7	341.5	391.5	336.7	376.4	365.9	348.9	318.8	348.3	353.49
48											

Table 20. Pay factors for quality assurance of asphalt concrete - example 1 (continued).

LINE NO.	M&C ITEMS	DESIGN VALUES	TEST DATA & SAMPLE NUMBER NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7	NO.8	TEST SAMPLE AVERAGE
49	CALCULATED PERFORMANCE CHARACTERISTICS										
50	* ESAL(THOUSANDS)	3266.5	2798.0	3166.1	3025.5	2968.9	2930.9	3043.2	2711.6	2882.[illegible]	2940.81
51	* YEARS	10.00	8.57	9.69	9.26	9.09	8.97	9.32	8.30	8.8[illegible]	9.00
52	* LOAD RATIOS	1.00	0.86	0.97	0.93	0.91	0.90	0.93	0.83	0.88	0.90
53	* MEAN SAMPLE LOAD RATIO	0.90									
54	* 100 % PAY LIMIT	0.85									
55											
56	QUALITY LEVEL COMPUTATIONS FOR PAY ADJUSTMENT FACTORS BASED ON TEST RESULTS										
57	* MEAN LIFE, YEARS	9.00									
58	* MEAN LOAD RATIO	0.90									
59	* NO. TESTS	8									
60	* LOAD RATIO STD. DEV.	0.0442									
61	* Q=(X-L)/S	1.1388									
62	* PL= %=>L (TABLE -)	85.5	FHWA TABLE 106-1								
63	* QUALITY LEVEL (FHWA)	85.5									
64	* PAY FACTOR (FHWA), %	101.3	FHWA TABLE 106-2								
65	* PAY FACTOR (FORMULA), %	97.8	FORMULA = 105-0.5*PD								
66											
67	COST ANALYSIS FOR PAY ADJUSTMENT FACTORS BASED ON AVERAGE TEST RESULTS										
68	* COST FACTORS										
69	** PRESENT UNIT COST	$3.50									
70	** OVERLAY UNIT COST	$3.50									
71	** OVERLAY LIFE, YEARS	10.00									
72	** INFLATION RATE, %	4.0									
73	** INTEREST RATE, %	8.0									
74	** R FUNCTION	0.96296									
75	* PAY ADJUSTMENT FACTORS										
76	** INDIVIDUAL YEARS	10.0	8.6	9.7	9.3	9.1	9.0	9.3	8.3	8.8	
77	** MEAN SAMPLE YEARS	9.0									
78	** 100 % PAY LIMIT, YEARS	10.0									
79	** PAY FACTOR, %	91.6									
80											

Table 21. Pay factors for quality assurance of asphalt concrete - example 2.

LINE NO.	M&C ITEMS	DESIGN VALUES	TEST DATA & SAMPLE NUMBER								TEST SAMPLE AVERAGE
			NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7	NO.8	
1	PROJECT ______										
2	DATE __/__/__ TIME __/__ AM/PM										
3	SAMPLE/CORE NO(S). ______										
4	LOCATION ______										
5											
6	PAVEMENT DESIGN FACTORS (AASHTO GUIDE)										
7	* ESAL/YEAR (THOUSANDS)	238.4	238.4	238.4	238.4	238.4	238.4	238.4	238.4		238.4
8	* INITIAL PSI	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2		4.2
9	* FINAL PSI	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5		2.5
10	* Z(R)	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3		-1.3
11	* S(O)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35		0.35
12	* SUBGRADE MODULUS,PSI	7500	7500	7500	7500	7500	7500	7500	7500		7500.00
13	* D1 (ASPH CONC), IN.	3.00	3.55	2.71	3.35	3.00	3.25	2.93	2.95		3.11
14	** A1	0.44	0.43	0.42	0.44	0.42	0.40	0.37	0.40		0.41
15	* D2 (ASPH CONC), IN.	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00		7.00
16	** A1	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30		0.30
17	* D3 (AGG BASE), IN.	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00		6.00
18	** A3	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11		0.11
19	* D4 (AGG BASE), IN.										
20	** A3										
21	* SN	4.07	4.27	3.90	4.24	4.01	4.06	3.85	3.94		4.04
22											
23	MATERIALS CHARACTERISTICS - ASPHALT CONCRETE										
24	* LAYER ______										
25	* ASPHALT (TYPE/PEN 77F)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		1.00
26	* ASPHALT CONTENT (%)	4.1	4.4	3.9	4.1	4.1	4.5	3.8	4.7		4.22
27	** UL										
28	** LL										
29	* AGGREGATE (TYPE ?)										
30	** MAX SIZE, IN.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		1.00
31	* AGG % <#4 SIEVE (JMF)										
32	** UL (JMF)										
33	** LL (JMF)										
34	* AGG % <#30 SIEVE (JMF)	15.4	17.3	16.3	16.2	16.8	16.5	18.0	15.7		16.69
35	** UL (JMF)										
36	** LL (JMF)										
37	* AGG % <#200 SIEVE(JMF)	3.0	4.1	3.3	1.8	2.8	2.2	2.4	2.3		2.70
38	** UL (JMF)										
39	** LL (JMF)										
40	* AIR VOIDS (%)	4.0	3.9	3.9	3.7	4.8	5.1	6.1	5.1		4.66
41	** UL (FIELD)										
42	** LL (FIELD)										
43	* VMA (%)	13.9	14.9	15.5	14.0	15.1	15.0	16.8	14.2		15.07
44	** UL (DESIGN)										
45	* ** LL (DESIGN)										
46	* COMPACTION INDEX	0.78	0.69	0.70	0.85	0.62	0.54	0.40	0.56		0.62
47	* RES MODULUS (MR,KPSI)	537.3	493.8	477.8	546.4	460.7	421.3	361.8	416.4		454.04
48											

Table 21. Pay factors for quality assurance of asphalt concrete - example 2 (continued).

LINE NO.	M&C ITEMS	DESIGN VALUES	TEST DATA & SAMPLE NUMBER NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7	NO.8	TEST SAMPLE AVERAGE
49	CALCULATED PERFORMANCE CHARACTERISTICS										
50	* ESAL(THOUSANDS)	3575.7	4868.7	2719.6	4583.3	3215.3	3504.1	2509.0	2868.1		3466.87
51	* YEARS	15.0	20.4	11.4	19.2	13.5	14.7	10.5	12.0		14.54
52	* LOAD RATIOS	1.00	1.36	0.76	1.28	0.90	0.98	0.70	0.80		0.97
53	* MEAN SAMPLE LOAD RATIO	0.97									
54	* 100 % PAY LIMIT	0.70									
55											
56	QUALITY LEVEL COMPUTATIONS FOR PAY ADJUSTMENT FACTORS BASED ON TEST RESULTS										
57	* MEAN LIFE, YEARS	14.54									
58	* MEAN LOAD RATIO	0.97									
59	* NO. TESTS	7.00									
60	* LOAD RATIO STD. DEV.	0.2581									
61	* Q=(X-L)/S	1.0444									
62	* PL= %=>L (TABLE -)	85.0	FHWA TABLE 106-1								
63	* QUALITY LEVEL (FHWA)	85.0									
64	* PAY FACTOR (FHWA), %	101.5	FHWA TABLE 106-2								
65	* PAY FACTOR (FORMULA), %	97.5	FORMULA = 105-0.5*PD								
66											
67	COST ANALYSIS FOR PAY ADJUSTMENT FACTORS BASED ON AVERAGE TEST RESULTS										
68	* COST FACTORS										
69	** PRESENT UNIT COST	$5.65									
70	** OVERLAY UNIT COST	$3.50									
71	** OVERLAY LIFE, YEARS	10.00									
72	** INFLATION RATE, %	4.0									
73	** INTEREST RATE, %	8.0									
74	** R FUNCTION	0.96296									
75	* PAY ADJUSTMENT FACTORS										
76	** INDIVIDUAL YEARS	15.0	20.4	11.4	19.2	13.5	14.7	10.5	12.0		
77	** MEAN SAMPLE YEARS	14.5									
78	** 100 % PAY LIMIT, YEARS	15.0									
79	** PAY FACTOR, %	98.1									
80											

testing of field samples. The computations are extremely sensitive to small changes in M&C properties, and inconsistencies between design and field sampling and testing will be reflected in the pay adjustment factors.

Lines 6 through 21 of the spreadsheet provide input for the AASHTO Guide procedure for structural design of flexible pavements. Provision is made for calculating SN for four pavement layers, plus subgrade. However, in this version of the spreadsheet the layer coefficient for only one asphalt concrete course can be modified by M&C variables.

As explained above, the layer subject to analysis is assumed to have a layer coefficient of 0.44. This value can be changed easily by the user by modifying the equation imbedded in line 14. For example, if a coefficient of 0.40 is used for the design value, the calculated ESAL would change, but the relative ESAL would not, because the calculation procedure is based on the ratio of MR values, not absolute values.

The other layers in tables 20 and 21 have been selected so that the example approximates an asphalt concrete overlay on an existing, heavily travelled pavement. If actual thicknesses are not available even for the layer for which acceptance is being determined, and sample data comes from loose mix samples and nuclear density tests taken in the field, then design thicknesses may be used. However, any effects of thickness, positive or negative, will not be reflected in the pay factors.

Line 23 begins the section of the spreadsheet provided for input of M&C data and calculation of requisite output, CI and MR. Provision is made for entering percents of aggregate passing the 3/4-inch (19-mm), No. 4 (4.75 mm), No. 30 (600 μm), and No. 200 (75 μm) sieves. However, only the No. 30 (600 μm) and No. 200 (75 μm) sieves are used in this version of the prediction models.

The mix designs shown in tables 20 and 21 were performed using a 75 blow Marshall test procedure. The calculated values for the compaction index CI of 0.75 and 0.78 respectively may be compared to values shown in tables 17 and 18 for other examples. The low CI values of 0.19 to 0.40 calculated for the field cores in table 20 largely reflect the high air voids and VMA values permitted by the compaction criteria. The example given in table 21 shows how CI improved on a project with a different mix.

Line 49 begins the section of the spreadsheet where performance characteristics are calculated. Line 50 gives total ESAL calculated using the AASHTO Design Guide equations with the appropriate input values derived from the CI and MR prediction equations. A terminal PSI of 2.5 was assumed in this example. A different terminal PSI could have been used by changing the input in line 9.

Line 51 is used to convert ESAL to years. Years is an input into one of the procedures for calculating pay adjustment factors. Line 52 is used to calculate the ratios between sample years and design years, for each individual sample. Line 54 is used to input the minimum value of the load ratio which pays 100 percent of the bid price. The remaining lines are used to compute pay factors using two different procedures.

PAY ADJUSTMENT FACTORS

Pay factors are an integral part of the proposed quality assurance procedures. Two basic procedures were investigated:

- Use of a statistical approach, based on the sample mean and standard deviation of test values from a given lot of asphalt concrete, to estimate the percent of predicted pavement life values that lie at or above a 100-percent pay limit. Pay factors are based on the percent life above the 100-percent pay limit.

- Use of the average of a set of predicted repetitions to some end point as the basis for performing an economic or life cycle cost analysis to determine pay factors.

The concepts of statistical quality assurance procedures that utilize lot sample means and standard deviations for acceptance and pay adjustment factors derived from a cost analysis are integral parts of the spreadsheets in tables 20 and 21. They have been adapted from work reported in references 32 and 33, and through personal contact with the authors.

The concept of using sample means and standard deviations for quality assurance also is included in reference 47 (FHWA method). Reference 47 includes a procedure for estimating the percent of a lot of material that lies within specification limits, plus pay factors. Tables 106-1 and 106-2 shown in lines 62 and 64 of the spreadsheets are from this reference.

Line 54 of the spreadsheet is the lower limit established for 100-percent pay. Line 56 begins a section in which the percent of the lot of material above the minimum requirement for 100 percent pay is calculated using sample means and standard deviations. Pay factors are determined from the quality level (QL) calculations in line 61 in two ways: from reference 47 tables and by using a formula to calculate pay factors (PF) directly from PL in line 62:

$$PF = 105.0 - 0.5(PD) \tag{34}$$

where PD = Percent defective or 100-PL
and PL = Percent of the lot within the 100 percent pay limit

The formula permits a maximum payment of 105 percent, and pays 100 percent if 90 percent of the lot is within the limits. A lot with no percent within the limit will be rejected or paid for at 55 percent. The FHWA method has a lower pay limit of 75 percent for rejection.

Line 67 marks the beginning of the calculation of pay adjustment factors based on an economic analysis of the relative cost of the design, or target, life versus the pavement life expected based on the test samples. The cost analysis equation, derived in reference 32, is as follows:

$$PF = 100*(1 + C_o*(R^{Ld}-R^{Le})/(C_p*(1-R^{Lo}))) \tag{35}$$

where PF = pay factor in percent
C_p = present unit cost of the pavement pay item

C_o = present unit cost of the overlay
L_d = design life of the pavement
L_e = expected life of the pavement
L_o = expected life of the overlay
$R = (1+R_{inf}/100)/(1+R_{int})$
R_{inf} = annual rate of inflation
R_{int} = annual rate of interest.

This equation was used in these examples to determine pay factors based on the average predicted lives of the pavement test sample, line 76. It does not take into consideration the distribution of field test samples.

CHAPTER 8. PROPOSED ADDITIONAL LABORATORY STUDY PROGRAM

INTRODUCTION

The scope of work for this project involved the planning of a laboratory study in two parts: the first outlining the part of the experiment that could be carried out within the time and funding allotted for a laboratory study, and a second part outlining a study which would require additional time and funding.

As explained in chapter 5, the objective of the laboratory program for this project was to obtain laboratory data that could be used to develop relationships between materials and construction (M&C) variables and performance-related asphalt mixture properties. The experiment designed to accomplish as much of this objective as possible, within the time and funding available, is summarized in tables 5 through 9, and figure 6. The experiment was designed as a one-sixth fractional factorial experiment with limited replication.

Dependent variables included resilient modulus and tensile strength determined on 108 combinations of independent M&C variables using an indirect tensile testing device. Fatigue parameters were determined on only 12 combinations of independent M&C variables. Creep factors were determined in direct compression on the same 12 combinations of M&C variables.

ADDITIONAL RESEARCH NEEDS

Results of the laboratory experiment indicated that additional research is needed in the following areas:

- Use of a full-factorial or, as a minimum, a one-half fractional experiment design to provide tests on more combinations of M&C variables than were included in the first experiment.
- Improved sample preparation procedures, including compaction and treatment of compacted specimens under elevated temperature conditions, to reduce data scatter.
- Studies of other factors that affect data scatter.
- A quantitative method for describing compaction effects on mixture properties.
- Tests on more asphalt and aggregate combinations, antistrip procedures, and aggregate gradations.
- More tests to define properties of the asphalts and aggregates.
- Tests at more temperature conditions.
- Reconsideration of mix design criteria and test procedures.
- Statistical analysis of the data using nonlinear analysis techniques.

DISCUSSION OF RESEARCH NEEDS

Experiment Design

Conducting a full factorial experiment for the variables included in the laboratory study of this project with partial replication would require in excess of 10,000 test specimens. The use of a one-sixth fractional factorial experiment design, with only a small percentage of tests devoted to fatigue and creep testing, required 1068 test specimens, and was a serious limitation. Although statistically sound, the experiment design appears to have allowed certain combinations of M&C variables to be represented by only a few tests. This has made it difficult to determine some relationships with the desired degree of statistical significance. It is recommended that further studies use a full, or at least a half fractional, factorial experiment design.

Operator and Testing Variability

Although the testing in this study was done in a research laboratory with proper certification, the test results exhibited a large amount of unexplained scatter, generally poor results were obtained for replicate tests, and a statistically significant effect was found for the time sequence in which certain operations were conducted. This indicates that more care needs to be taken to locate and overcome factors that contribute to operator and testing variability. An experiment to define causes, and propose corrections, should be a significant part of any new laboratory study.

Compaction of Test Specimens

It is generally agreed that laboratory compaction procedures do not reproduce field compaction to a high degree. Several compaction procedures to overcome this difficulty have been proposed. The kneading compactor used in this study has a long history of use, and is considered quite good by many researchers. The Asphalt-Aggregate Mixture Analysis System (AAMAS) study has used a gyratory compaction procedure with moderate success. The Strategic Highway Research Program (SHRP) Asphalt Project A003A has proposed the use of a European procedure whereby test specimens are cut from oversize samples prepared in a rolling wheel compaction device. For field laboratory use, a commercially available gyratory compaction device may prove the best compromise.

Regardless of the procedure used, however, the laboratory study conducted for this project showed that compaction has a highly significant impact on test results. The results indicated that there is a high degree of interaction between compactive effort and other mix variables. It seems obvious, therefore, that problems with laboratory compaction could be a major impediment to the successful implementation of performance-related specifications. There is a great need to be able to compact specimens in the laboratory in a way that can be related to field compaction. Research into laboratory compaction procedures, the interaction effects of other M&C variables on compaction and the relationship of laboratory procedures to compaction in the field need further research attention.

Mix Design

The AAMAS and SHRP A003A projects are developing mixture analysis procedures that are supposed to provide performance-related mix designs. The commonly used Marshall and Hveem mix design procedures are known to have high between-laboratory variability, which can result in controversy between contractors and contract agencies. Also, use of two different procedures with the same materials will produce different mix designs. Along with the procedures themselves, the criteria used to select design proportions differ between agencies, and can not be related directly to performance in any case.

It is proposed in this report that performance-related asphalt mixture properties, such as resilient modulus, be estimated in the field using equations developed in laboratory studies. Properties could be obtained for optimum conditions from job-site testing with actual materials from the job. Pavement properties such as VMA could be obtained from pavement cores. Resilient modulus could be measured, but more time-consuming tests such as measuring fatigue resistance would not be.

It is likely that contracting agencies will want to continue to use relatively simple mix design procedures and apply established criteria to define an acceptable product. If this is to be done at the field level, to provide timely response during construction, a relatively simple mix design procedure needs to be available. Equations such as those developed in this study could provide an adequate substitute for mix design tests after they have been validated.

Continued development of performance-related specifications should include a study of mix design procedures and mix design criteria, as well as continued refinement and validation of performance models such as those developed in this project.

Materials

This study examined only a limited number of the materials available in the United States, but did include a range in asphalt content, a range in percents passing two sieves included in gradation analyses of aggregates, and a wide range in percent VMA and air voids in the compacted mix. Additional research is needed to characterize more materials, and to better define the properties that affect performance-related mixture properties.

Experiment Design Factors

Handling and testing specimens compacted at low compactive effort and conditioned at high temperatures was a problem in this study. In addition, except where field practices are extremely poor, the range in VMA achieved in the study exceeds to some extent the range likely to be obtained in actual practice. Any new laboratory study may need to restrict the low compactive effort somewhat more than was done in this study to help reduce variability in test results.

In this regard, it is highly recommended that additional analyses be made of the data generated in this study to determine more precisely the levels of each variable that are likely to yield the most consistent results.

CHAPTER 9. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

This project included a laboratory investigation into the effects of different M&C variables on performance-related properties of AC mixtures.

The following variables were included in the study:

- Two different asphalt sources: a Boscan and a California Valley crude source.
- Two different aggregates, one with a history of good stripping resistance, the other poor.
- Three asphalt contents: optimum, 0.75 above optimum and 0.75 below optimum.
- Use of lime as an antistripping agent.
- Compaction level to vary voids and related properties.
- Percent passing the sieve No. 30 (600 μm), at three levels.
- Percent passing the sieve No. 200 (75 μm), at three levels.

Measurements included:

- Resilient modulus and tensile strength before and after aging in an oven, at two different temperatures, determined with an indirect tensile testing device.
- Resilient modulus and tensile strength before and after moisture conditioning according to a modified Lottman procedure, determined with an indirect tensile testing device.
- Deformation in uniaxial compression.
- Fatigue resistance determined with an indirect tensile testing device.

The experiment was a one-sixth fractional factorial design, in which 108 combinations out of a total of 648 were tested. Test data from the experiment were analyzed with the SPSS/PC statistical analysis program, using a stepwise multiple regression technique to find statistically significant variables. Prediction equations were determined by multiple regression using variables selected from the stepwise analysis and engineering experience.

The prediction equations determined in the study can be used:

- To adjust resilient modulus, tensile strength and fatigue resistance, determined for optimum conditions, for variations in aggregate gradation, asphalt content and compaction that occur at the job site.

- To estimate the effects of proposed changes in materials, specification limits or mix design criteria on asphalt mixture structural properties.

In addition, this study includes demonstration performance-related specifications (PRS's) for asphalt concrete developed using a computerized spreadsheet program. The description of the spreadsheet program addresses many of the significant factors that ought to be considered in assessing contractor bonuses and payment reductions. The sample PRS presented only considers serviceability history in the analysis process and is based on the AASHTO Guide procedure for structural design of flexible pavements. Pay factors were determined using different methodologies (e.g., NJDOT, FHWA).

CONCLUSIONS

The following conclusions can be drawn from the laboratory data:

1. The two different asphalts included in the study produced widely different resilient modulus and tensile strength values for the same conditions of test.

2. Compaction level had more influence on mixture properties than any other variable in the experiment.

3. Voids in the mineral aggregate and percent air voids were influenced more by compaction level than by mixture variables.

4. Fatigue life and indirect tensile strength were correlated.

5. Resilient modulus and indirect tensile strength also were correlated.

6. There is more variability in resilient modulus for a percent air voids less than 9 percent than above 9 percent. Variables other than air voids (e.g., asphalt type, asphalt content, aggregate gradation) are, therefore, more important in predicting resilient modulus for a percent air voids less than 9 percent. Percent air voids above 9 percent seems to be the most important variable to explain consistently low resilient modulus values.

7. Resilient modulus and tensile strength were related to materials and construction variables by equations that included interaction terms.

8. The most variable results were obtained for age-hardened and moisture-conditioned specimens.

9. The least variable results were obtained on unconditioned resilient modulus and tensile strength test specimens.

10. Variability in the test data appeared to contribute to the low level of statistical significance in many of the analyses.

11. Some of the variability appeared to be related to specimen preparation and testing techniques, operator variability or similar laboratory factors.

12. The poor fit of some of the equations to the data, and lack of statistical significance of some of the experimental factors, indicate that nonlinear modeling techniques may be required to derive better prediction equations from the data.

13. Some variables in the experiment, such as aggregate type and use of antistrip additive, were not described by numeric values. Equations derived by regression analysis that include aggregates and other variables described by non-numeric variables are difficult to extrapolate to other materials.

14. A technique for estimating compaction effects using measurable specimen properties was found.

15. The prediction equations can be used with an estimated compaction index to relate measured mixture properties to optimum properties.

16. A technique is proposed for estimating the effects of deviations from mix design or optimum conditions on performance-related mixture properties, using prediction equations with job-site calculations and job-site laboratory data from actual materials or core samples.

17. In a similar manner, the equations can be used to predict relative effects of proposed changes in materials and construction specifications on performance-related mixture properties.

18. When used with equations that relate performance-related mixture properties to pavement performance, the equations derived in this study can be used to establish penalties for nonconformance to specification limits.

19. In a similar manner, the equations can be used to modify specification limits and mix design criteria.

20. The significant effect of compaction on mixture strength properties indicates that further research is needed on specimen preparation procedures used in current laboratory practice.

21. The same observation points to a need to give a critical review to current field compaction criteria.

LIMITATIONS OF THIS STUDY

Because of the large number of experimental variables included in the laboratory experiment and because of time and funding limitations, many combinations of experimental variables were excluded. This factor, combined with a fairly large element of testing variability, contributed to a low degree of statistical significance in many of the relationships developed from the data from this project.

An assumption was used in planning this experiment that varying compaction effort would produce an orderly variation in specimen percent air voids. Unfortunately, this proved not to be the case. The interaction between compaction effort and other experimental variables was much more complicated, and affected the performance-related mixture properties in ways that complicated the development of prediction models.

It is not entirely clear that the indirect tensile test procedure adopted for this study produces absolute values equal to those that would have been obtained by other procedures. However, the test is popular and can be used to produce relative effects of different M&C variables on performance-related asphalt mixture properties using the techniques proposed in this report.

The prototype PRS system developed using Lotus 1-2-3 only considers serviceability history in the analysis process. The implemented method is based on the AASHTO Guide procedure for structural design of flexible pavements. Pay factors were determined using two different methodologies, NJDOT- and FHWA-recommended pay factor formulas.

RECOMMENDATIONS

The following recommendations are made, based on findings in this study:

1. The effects of specimen preparation and testing variability on test results found in this study should be investigated.

2. Future experiments should be conducted using full-factorial or, as a minimum, half-factorial experiment designs.

3. Additional laboratory studies should be conducted with:

   - Asphalts and aggregates from additional sources.

   - Use of different antistripping additives, with variable dosages.

   - A wider range of aggregate gradations.

4. Models developed in this study should be compared to models developed in other studies.

5. The data obtained in this study, and in future studies, should provide for obtaining quantitative data on asphalt and aggregate properties that can be included in prediction equations.

6. The effects of compaction effort and laboratory compaction procedures on percent air voids and VMA of test specimens should be further investigated.

7. Interactions between laboratory compaction procedures and other mixture variables, such as aggregate gradation factors, should be the subject of further research.

8. A laboratory compaction procedure, perhaps using a small, commercially available gyratory compactor, should be adopted for use in field laboratories.

9. Research, conducted as part of the AAMAS study, into relationships between laboratory compaction and field compaction should be continued.

10. The data obtained in this study, and data from the NCHRP 10-26A study and other sources, should be used to develop nonlinear models that will better describe the effects of materials and construction variables on performance-related properties of AC mixtures.

11. The sample PRS presented in this study need to be extended to consider more types of distress than just serviceability.

12. Different pay schedules were obtained using the NJDOT and FHWA methodologies. It is therefore recommended that existing methodologies to determine pay schedules be further studied to establish the best-suited for asphalt concrete pavements.

APPENDIX A
SUMMARY OF SECONDARY PREDICTION RELATIONSHIPS

A. Prediction of Mix Stiffness.[26]

$$S_M = S_B \left[1 + \frac{2.5}{K} \frac{V_{AG}}{(1-V_{AG})} \right]^K$$

R^2 = ?? SEE = ?? n = ??

S_M = stiffness modulus of the mix (N/m^2)

S_B = stiffness modulus of the bitumen (N/m^2)

V_{AG} = volume concentration of the aggregates

$$K = 0.83 \ \text{Log} \ \frac{4 \times 10^{10}}{S_B}$$

B. Prediction of Dynamic Modulus.[26]

General form:

$$|E^*| = f\,(P_{200},\ f,\ V_v,\ \eta_{70o},\ t,\ V_b)$$

R^2 = ?? SEE = ?? n = ??

$|E^*|$ = absolute value of the complex modulus of the mix, psi

P_{200} = percentage of aggregate passing a #200 sieve

f = frequency of loading, Hz

V_v = percent air voids

η_{70o} = asphalt original absolute viscocity measured at 70 °F, 10^6 poises

t = temperature, °F

V_b = percent volume of binder

See figure 28 - Comparison of measured dynamic modulus with predicted modulus from Asphalt Institute equation.[26]

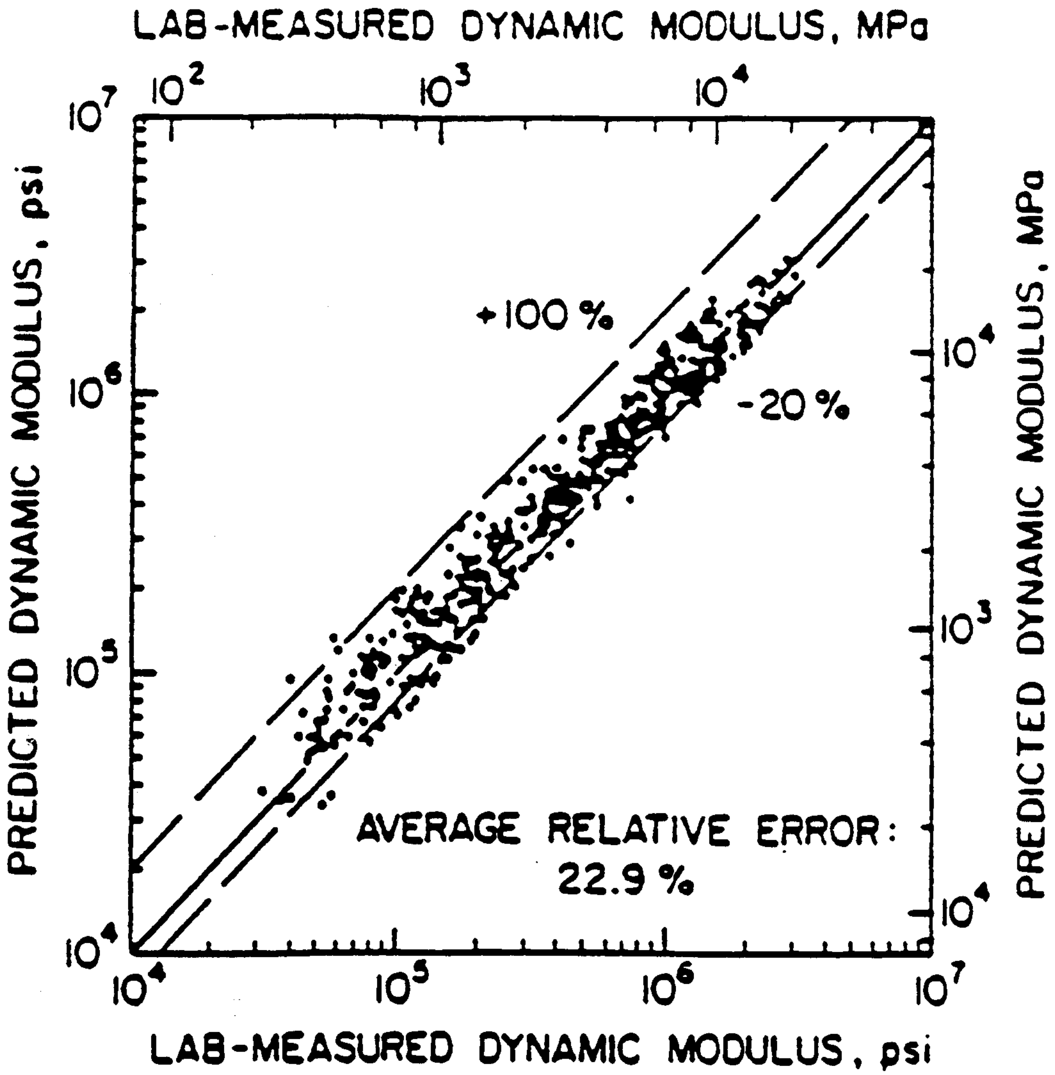


Figure 28. Comparison of measured dynamic modulus with predicted modulus from Asphalt Institute equation.(26)

C. Prediction of the Asphalt Modulus [AASHO Road Test via Ullidtz and Larsen[27]].

$E_1(t) = 15000 - 7900 \log t^o \quad t^o > 1\ ^\circ C$

$R^2 = ??$ SEE = ?? n = ??

$E_1(t)$ = asphalt modulus, MPa

t^o = temperature, °C

D. Prediction of Field Density [ASTM Standard Test Method via Papagiannakis and Haas[28]].

$PFD = 97.378 + 0.029\ GTMR - 6.045 \times 10^{-5}\ (GTMR)^2$

$R^2 = ??$ SEE = ?? n = ??

PFD = Density expressed in percent of the field density

GTMR = number of GTM revolutions

E. Prediction of Mix Stiffness [Shell Pavement Design Method via Papagiannakis and Haas[28]].

See figure 29 - Relationship between mix and bitumen stiffness.

$R^2 = ??$ SEE = ?? n = ??

F. Prediction of Bituminous Mix Stiffness [Bonnaure via Anderson et al.[26]].

See figure 30 - Nomograph for predicting bituminous mix stiffness.

$R^2 = ??$ SEE = ?? n = ??

G. Prediction of Mixture Stiffness [Epps and Monismith[29]].

See figure 31 - Relationship between initial stiffness modulus and asphalt content - California medium grading, basalt aggregate, 60-70 penetration asphalt.

$R^2 = ??$ SEE = ?? n = ??

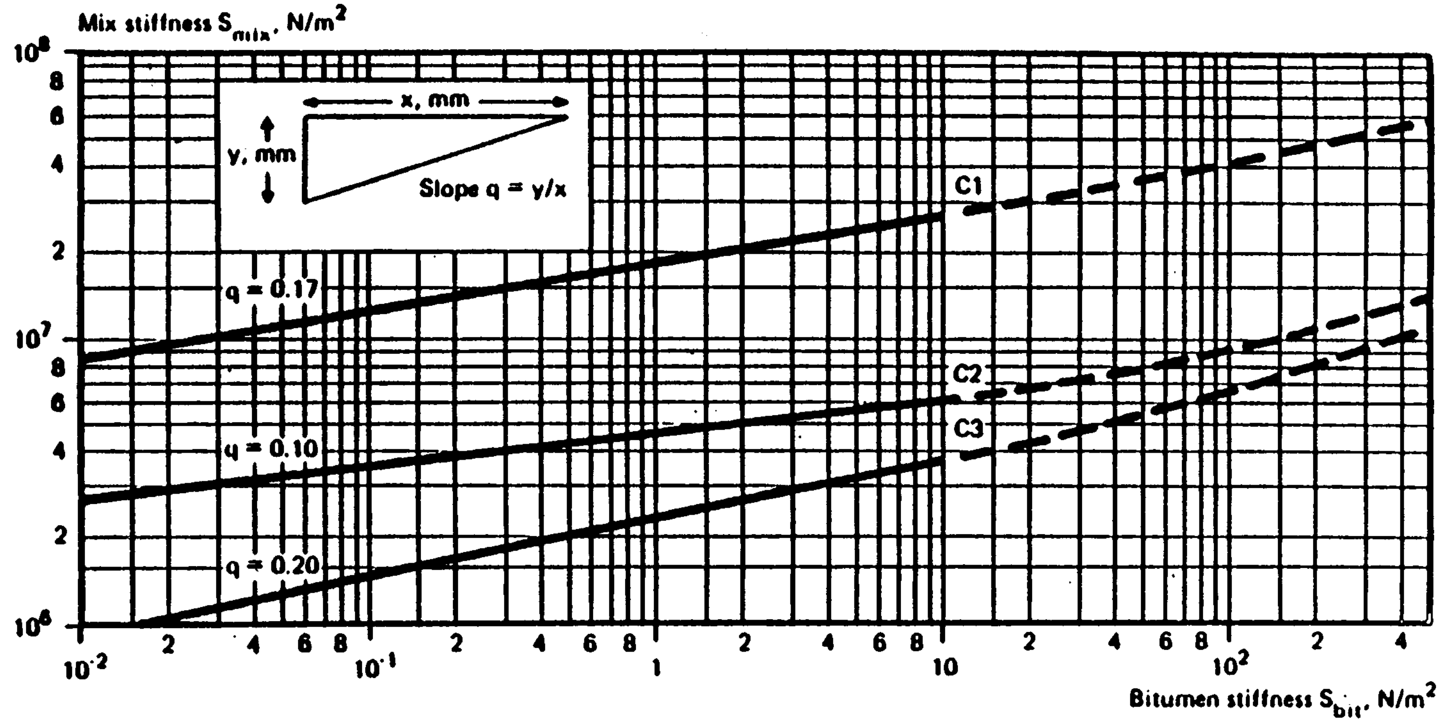


Figure 29. Relationship between mix and bitumen stiffness.(28)

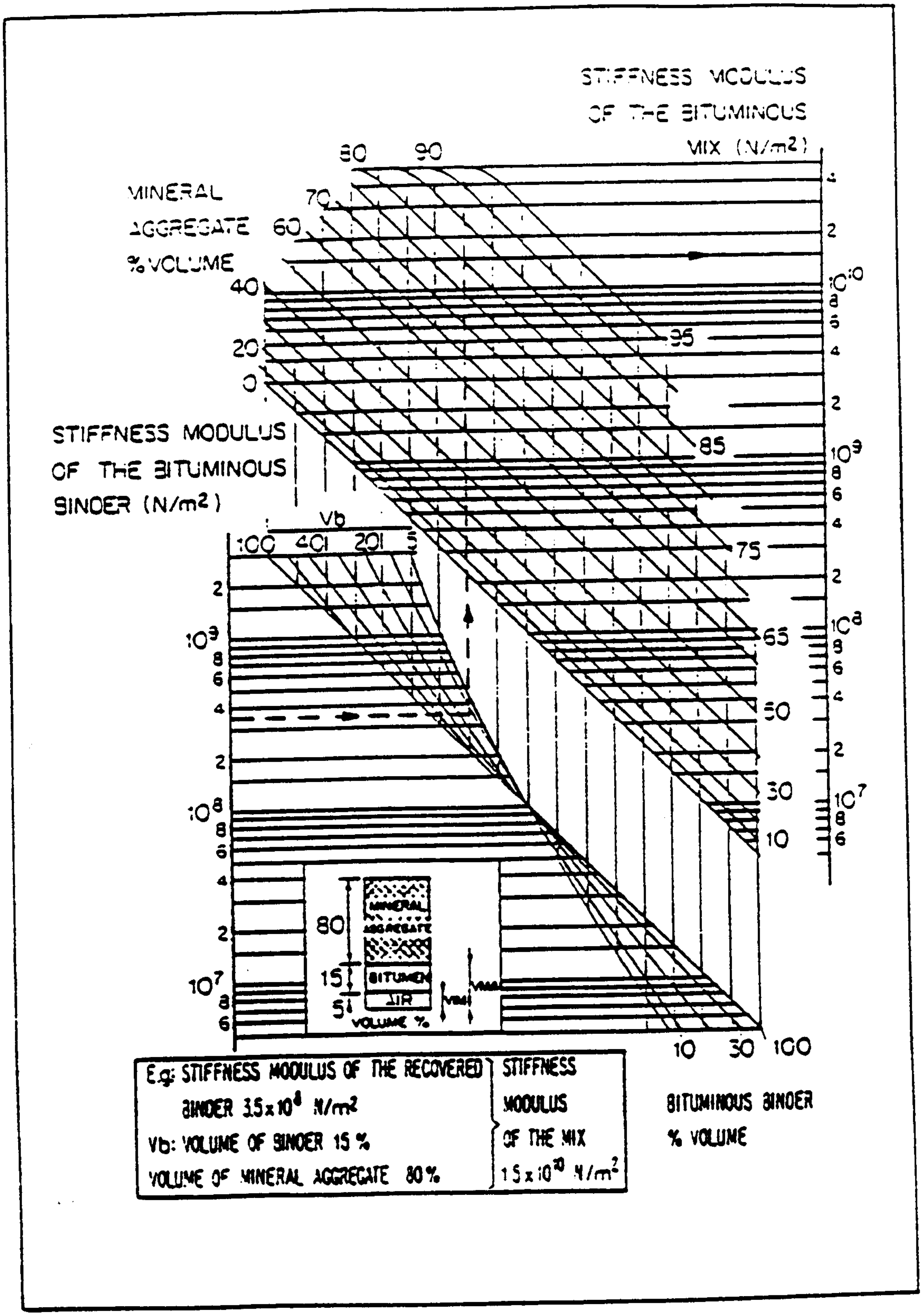
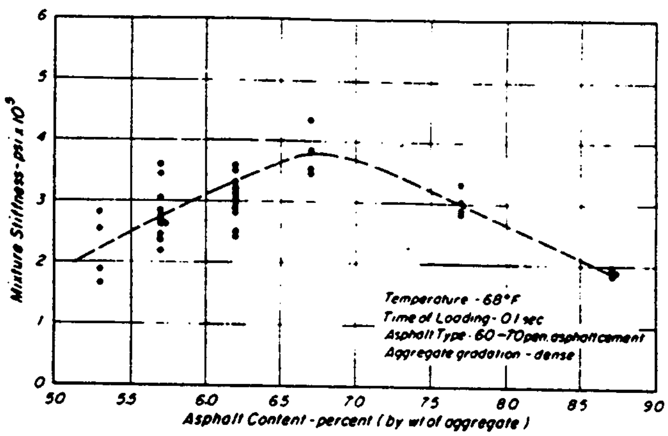


Figure 30. Nomograph for predicting bituminous mix stiffness.[26]

MIXTURE FATIGUE



1 psi = 6.89 kPa

Figure 31. Relationship between initial stiffness modulus and asphalt content - California medium grading, basalt aggregate, 60-70 penetration asphalt.(29)

H. Prediction of Initial Stiffness Modulus.[29]

See figure 32 - Relationships between initial stiffness modulus and air void content - granite aggregate.

R^2 = ?? SEE = ?? n = ??

I. Prediction of Marshall Stability, Hveem Stability and Relative Density.[30]

See figure 33 - Design curves for black base.

R^2 = ?? SEE = ?? n = ??

J. Prediction of Total Deflection at Failure.[30]

$Y_{est} = 3.0075 - 2.1307\ X_1 + 0.0326\ X_2$

$R^2 = 0.797$ SEE = 0.048 n = ??

Y_{est} = total deflection at failure

X_1 = specimen thickness

X_2 = specimen temperature

See figure 34 - Total deflection at failure versus specimen thickness and specimen temperature.

K. Prediction of Dynamic Modulus of Elasticity at Failure.[30]

$\text{Log } Y_{est} = 7.1440 - 0.2412\ X_1 - 0.0207\ X_2$

$R^2 = 0.931$ SEE = 0.0728 n = ??

Y_{est} = dynamic modulus of elasticity at failure

X_1 = specimen thickness

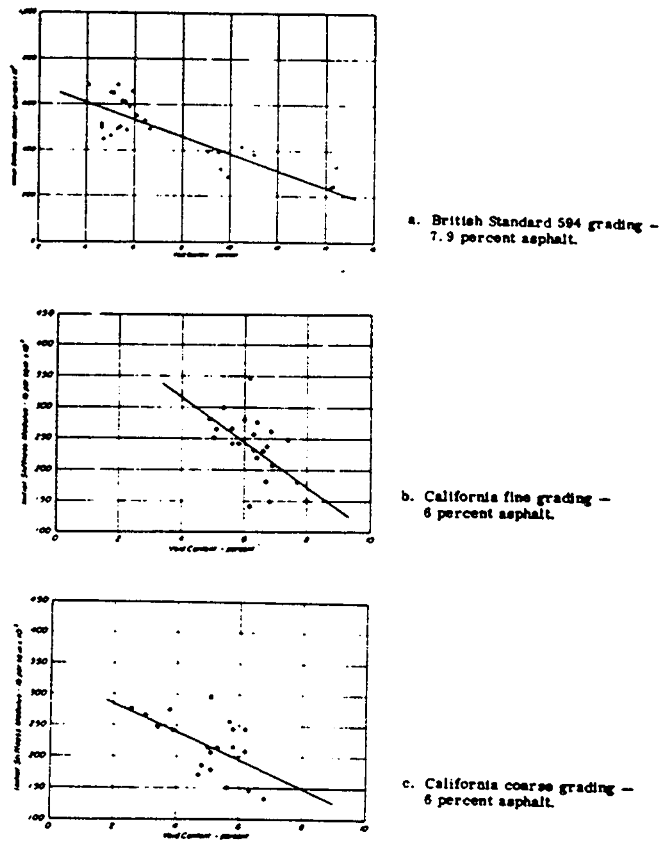
X_2 = specimen temperature

See figure 35 - Dynamic modulus of elasticity at failure versus specimen thickness and specimen temperature.

L. Prediction of Resilient Modulus [Finn et al., via Shook and Kallas[31]].

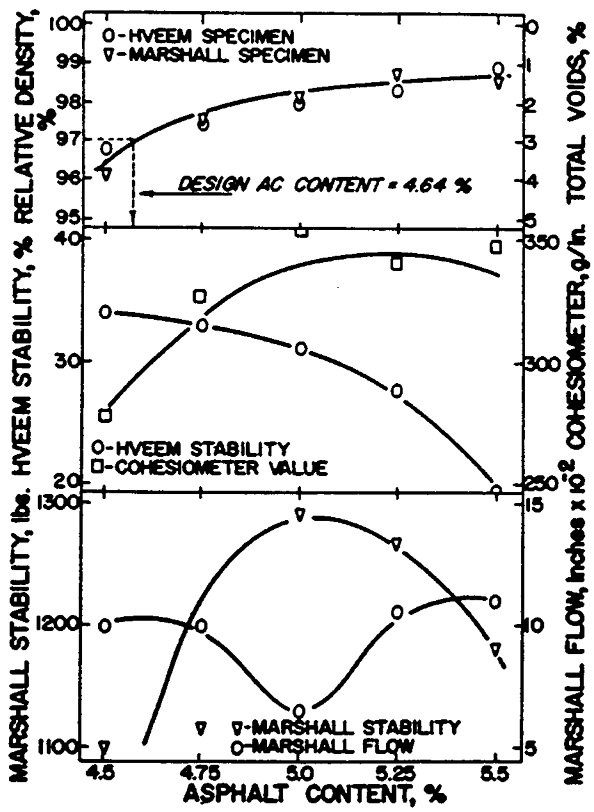
$\ln M_r = 1.86 - 0.016\ \text{PEN} + 0.047\ \text{DENS} + 2.58\ \text{PSAND}$

$R^2 = 0.659$ SEE = 0.680 n = 35



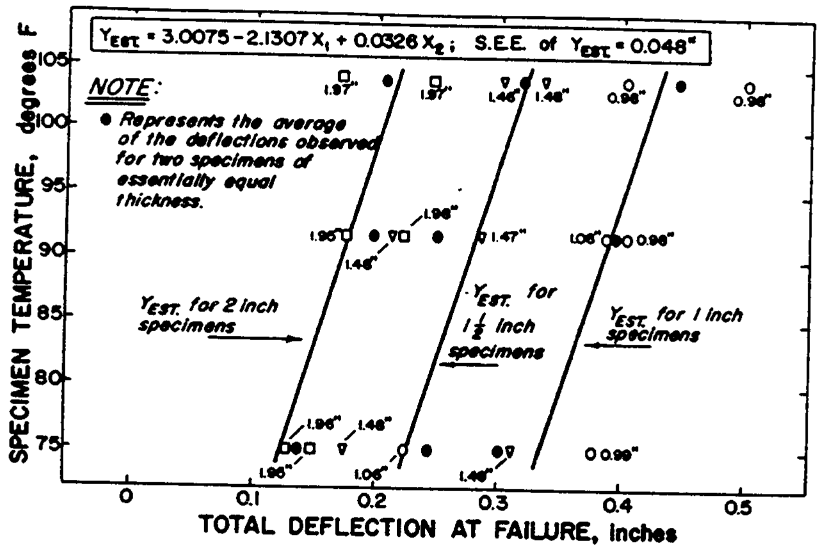
1 psi = 6.89 kPa

Figure 32. Relationships between initial stiffness modulus and air void content - granite aggregate.(29)



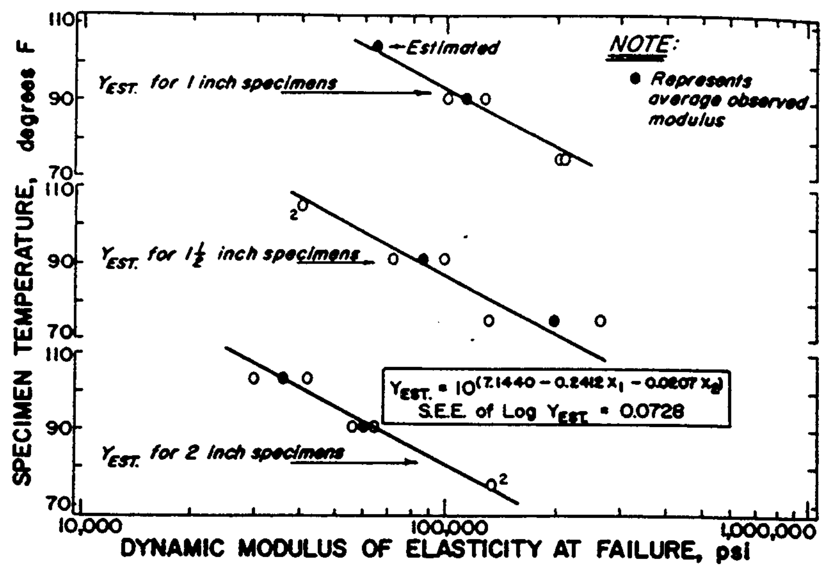
1 in = 25.4 mm
1 lb = 0.454 kg

Figure 33. Design curves for black base.[30]



°C = 5(°F-32)/9
1 in = 25.4 mm

Figure 34. Total deflection at failure vs specimen thickness and specimen temperature.(30)



°C = 5(°F-32)/9
1 in = 25.4 mm
1 psi = 6.89 kPa

Figure 35. Dynamic modulus of elasticity at failure vs specimen thickness and specimen temperature.[30]

M_r = resilient modulus x 10^{-3}

PEN = penetration

DENS = density

PSAND = percent of sand in the aggregate

M. Prediction of Dynamic Modulus.[31]

$$\text{Log}_{10}/E^*/ = 1.54536 + 0.020108\ (X_1) - 0.0318606\ (X_2) + 0.068142\ (X_3) - 0.00127003\ (X_4)^{0.4}(X_5)^{1.4}$$

$R^2 = 0.968$ SEE = 0.0888904 n = ??

$/E^*/$ = dynamic modulus, 10^5 psi (4 cps loading frequency)

X_1 = percent minus #200 material in the aggregate

X_2 = percent air voids in the mix

X_3 = asphalt viscosity at 70 °F, 10^6 poises

X_4 = percent asphalt by weight of mix

X_5 = test temperature, °F

X_6 = $\log_{10}$ viscosity of asphalt at test temperature, poises

---

N. Prediction of Dynamic Modulus.[31]

$$\text{Log}_{10}/E^*/ = 3.12197 + 0.0248722(X_1) - 0.0345875(X_2) - 9.02594(X_4)^{0.19}/(X_6)^{0.9}$$

$R^2 = 0.971$ SEE = 0.0849186 n = ??

$/E^*/$ = dynamic modulus, 10^5 psi (4 cps loading frequency)

X_1 = percent minus #200 material in the aggregate

X_2 = percent air voids in the mix

X_3 = asphalt viscosity at 70 °F, 10^6 poises

X_4 = percent asphalt by weight of mix

X_5 = test temperature, °F

X_6 = $\log_{10}$ viscosity of asphalt at test temperature, poises

---

O. Prediction of Dynamic Modulus.[31]

$$Log_{10}/E^*/ = -0.124262 + 1.25469(K) - 0.0616215(V)$$

R^2 = 0.900 SEE = 0.151416 n = ??

$/E^*/$ = dynamic modulus, 10^5 psi (4 cps loading frequency)

K = $\log_{10}$ of Marshall stability (lbs.) divided by 100 times Marshall flow (0.01 in.)

V = percent air voids for the modulus specimen minus percent air voids for the Marshall test specimen

---

P. Prediction of Dynamic Modulus.[31]

$$Log_{10}/E^*/ = 0.0983861 + 0.00351866(U) - 0.052137(V)$$

R^2 = 0.744 SEE = 0.284357 n = ??

$/E^*/$ = dynamic modulus, 10^5 psi (4 cps loading frequency)

U = ultimate tensile strength in psi (2 in./min.)

V = percent air voids for the modulus specimen minus percent air voids for the tensile specimen

---

Q. Prediction of Load Cycles to Laboratory Fatigue Failure [From Cooper and Pell via Anderson et al.[26]].

$$\text{Log } N = 4.13 (\text{Log PVB}) + 6.95 (\text{Log RBS}) - 11.13$$

R^2 = 0.88 SEE = ?? n = ??

N = number of allowable applications for a strain level of 1×10^{-4} in/in

PVB = percentage volume of binder

RBS = ring and ball softening point (°C)

APPENDIX B
MIX DESIGN PROGRAM

INTRODUCTION

The objective of this research program was to link the most common current specification parameters to pavement performance. This link between current specification parameters and pavement performance will be developed by measuring the impact of the parameters on fundamental mixture properties such as resilient modulus, tensile strength, permanent deformation, and fatigue characteristics. These fundamental properties could then be used in existing empirical and mechanistic pavement performance models to estimate rutting, fatigue cracking, and thermal cracking.

The primary variables considered in the scope of this project:

- Aggregate gradations (Maximum density, and above and below maximum density).
- Percent of minus No. 200 (75 μm) at three levels: 0, 6, and 12 percent.
- Stripping versus nonstripping aggregate.
- Temperature susceptibility of asphalt cement.
- Level of compactive effort.
- Asphalt content (optimum, and ±0.75 percent of optimum).

Secondary variables that were measured, but not controlled because they are linked to one or more of the primary variables, are:

- Voids in mineral aggregates.
- Air voids.

The impact of these variables on fundamental properties of unconditioned, as well as moisture-conditioned, and aged samples were determined.

The purpose of this appendix is to define the selection of the optimum asphalt content, and hence the values for the ±0.75 percent of optimum values for each gradation for each aggregate source. The results presented in this appendix were used throughout the remainder of the testing program.

MATERIALS

The materials described in this section were used throughout the research program.

Binders

Two asphalt cements were used:

- AC-20 from Amoco Oil Co., Savannah, Georgia.
- AR-4000 from Witco's Golden Bear Division, Oildale, California.

The physical properties, as supplied by the refineries, are shown in table 22.

Aggregates

Two Strategic Highway Research Program (SHRP) aggregate sources were selected for this research program. These were:

- Granite Rock Company, Watsonville, California.
- Vulcan Materials Company, Grayson, Georgia.

The Watsonville aggregate is a 100 percent crushed granite and paving projects constructed with this aggregate have not shown evidence of stripping. The Georgia aggregate, referred to as Lithonia granite, is also a 100-percent crushed granite. However, paving projects constructed with this aggregate source have indicated problems with stripping.

The physical properties for both aggregates are shown in table 23.

Gradations: Each aggregate source was sieved into individual fractions and then recombined to produce nine different gradations. These nine gradations selected were based on three basic gradations within a typical 3/4-in (19-mm) nominal maximum size, dense-graded paving mixture specification band. The basic gradations represent gradations closely following the:

- Maximum density line.
- Above maximum density line (i.e., top of specification band).
- Below maximum density line (i.e., bottom of specification band).

The minus No. 200 (75 μm) material was then varied for each of these gradations. These variations resulted in a total of nine gradations (table 24 and figures 36, 37, and 38). Three gradations theoretically contain no minus No. 200 (75 μm) material; therefore all aggregates used to prepare these samples were washed and oven-dried prior to use in sample preparation.

Once the aggregate was prepared, one sample from each gradation for each aggregate source was batched and the actual gradation was checked by performing a washed sieve analysis. The results of this check are shown in tables 25 and 26. The variations between the actual gradation and the target gradation were compared using the acceptable ranges for two test results, single-operator and multilaboratory, described in the ASTM C136 precision statement. Since more than one operator, using different sieve

Table 22. Physical properties of asphalt cements.

Physical Property	Witco AR 4000	Amoco AC-20
Viscosities:		
140 °F, Poise	2200	2107
275 °F, cSt	260	NA
Penetration:		
77 °F, 5 sec./100g	51	87
Flash Point, °C	260	268
Specific Gravity	1.0256	NA
Ductility	NA	NA
Rolling Thin Film:		
Weight Loss, %	0.2	
Viscosities:		
140 °F, Poise	4000	
275 °F, cSt	350	
Penetration:		
77 °F, 5 sec./100g	34	
Ductility	150+	

°C= 5(°F-32)/9

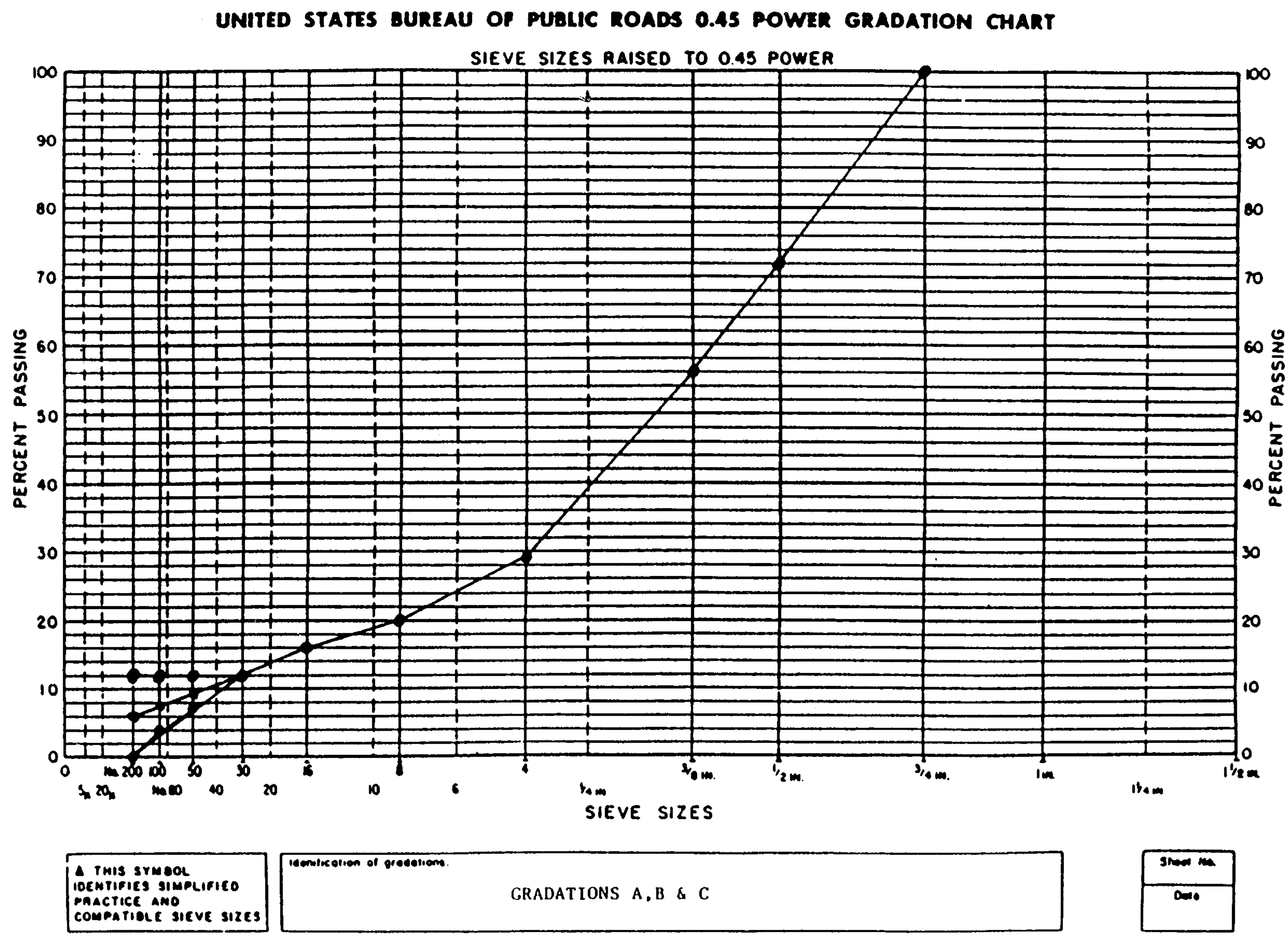
Table 23. Physical properties for Lithonia granite (stripper) and Watsonville granite (nonstripper).

Physical Properties	Lithonia Granite		Watsonville Granite	
	Coarse	Fine	Coarse	Fine
Bulk Specific Gravity	2.630	2.640	2.682	2.589
Bulk Specific Gravity, SSD	2.643	2.644	2.735	2.667
Apparent Specific Gravity	2.663	2.651	2.832	2.806
Absorption Capacity %	0.5	0.2	2.0	3.0

Table 24. Target gradations for samples.

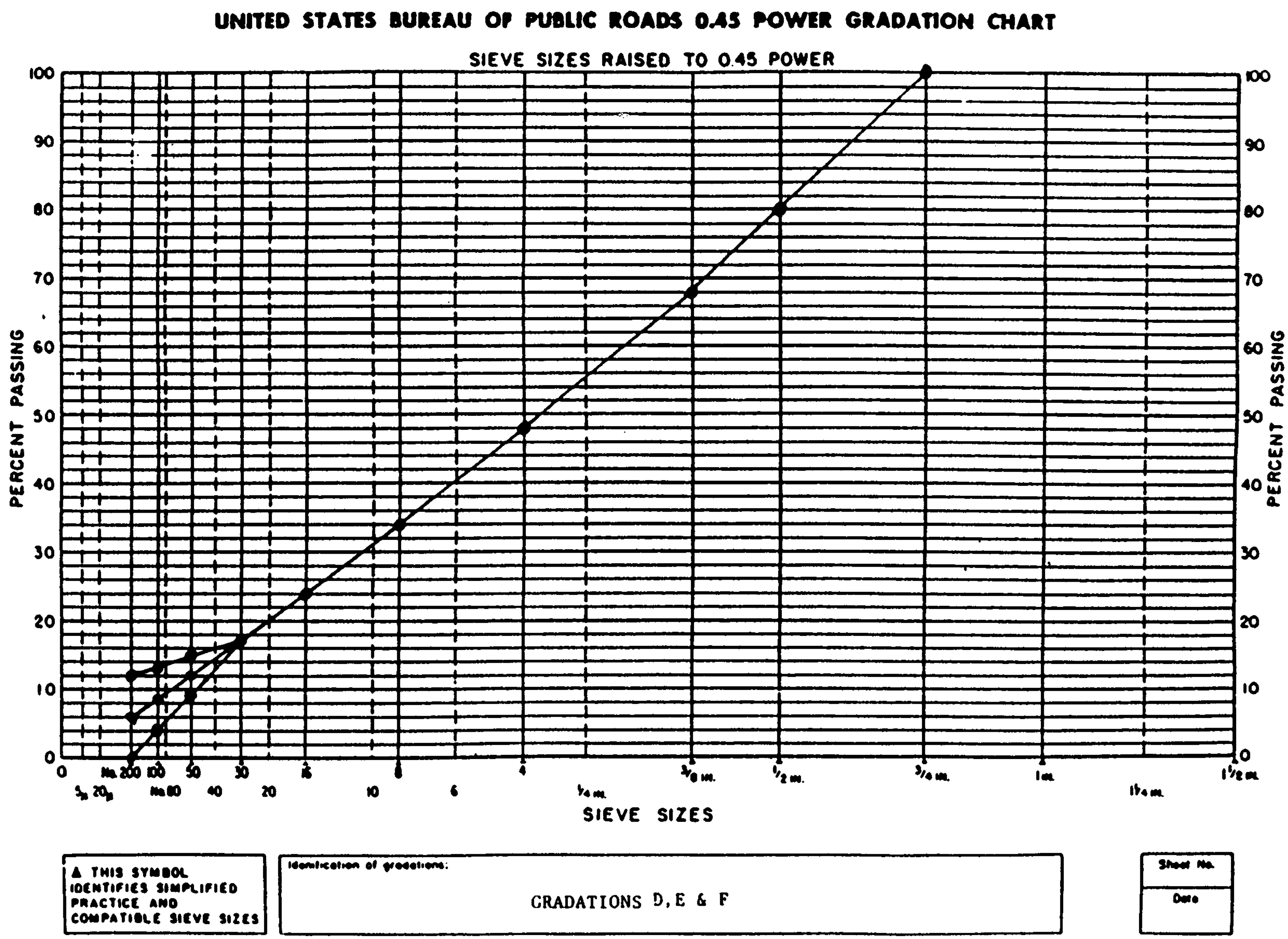
Sieve No.	Gradation								
	A	B	C	D	E	F	G	H	I
	Percent Passing, (%)								
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	72.0	72.0	72.0	80.0	80.0	80.0	85.0	85.0	85.0
3/8 in	56.0	56.0	56.0	68.0	68.0	68.0	76.0	76.0	76.0
No. 4	29.0	29.0	29.0	48.0	48.0	48.0	62.0	62.0	62.0
No. 8	20.0	20.0	20.0	34.0	34.0	34.0	50.0	50.0	50.0
No. 16	16.0	16.0	16.0	24.0	24.0	24.0	39.0	39.0	39.0
No. 30	12.0	12.0	12.0	17.0	17.0	17.0	30.0	30.0	30.0
No. 50	7.0	9.5	12.0	9.0	12.0	15.0	16.0	19.0	22.0
No. 100	4.0	8.0	12.0	4.0	8.5	13.0	7.5	12.0	16.0
No. 200	0.0	6.0	12.0	0.0	6.0	12.0	0.0	6.0	12.0

1 in = 25.4 mm



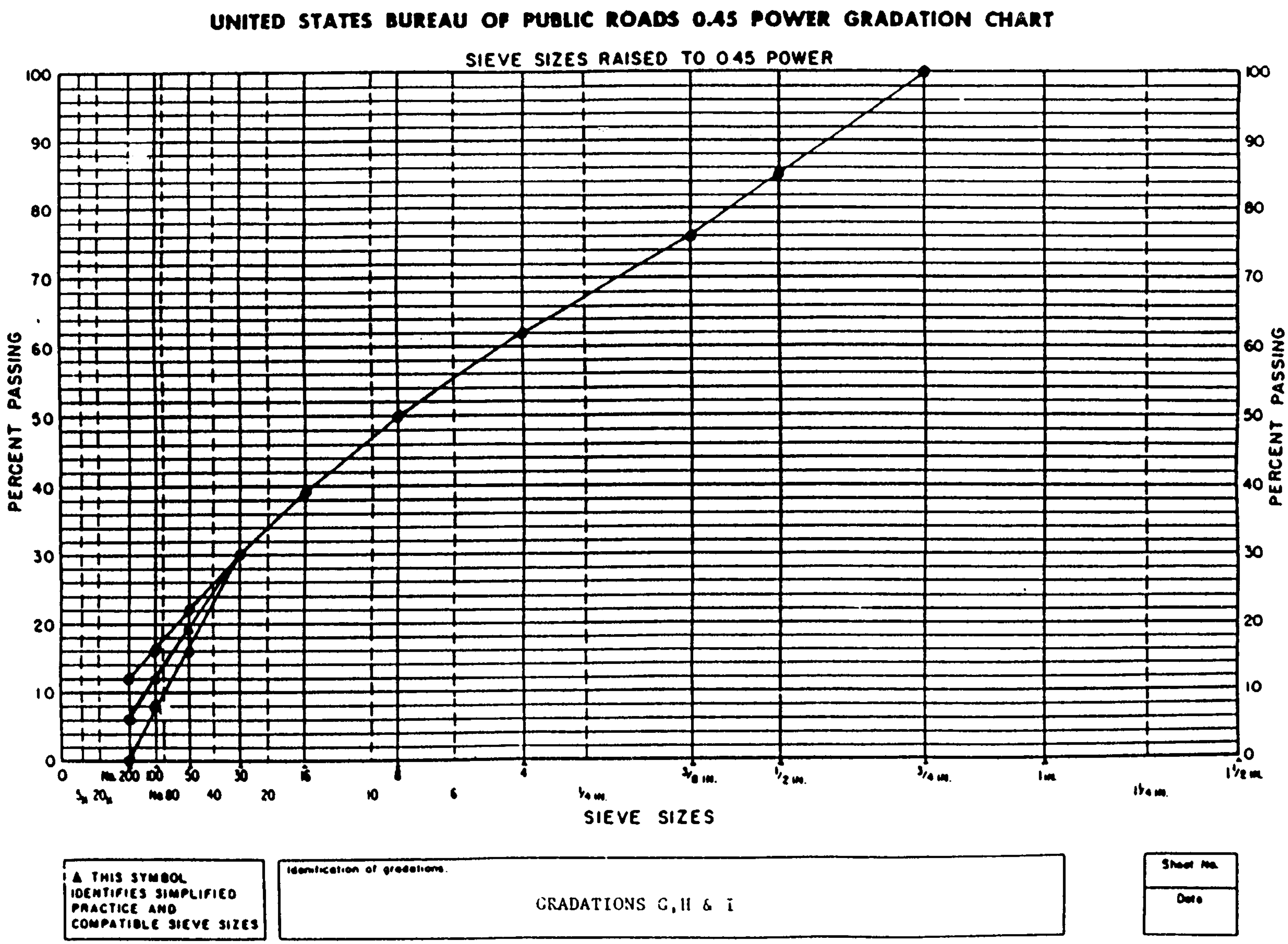
1 in = 25.4 mm

Figure 36. Gradations a, b & c.



1 in = 25.4 mm

Figure 37. Gradations d, e & f.



1 in = 25.4 mm

Figure 38. Gradations g, h & i.

Table 25. Actual gradations obtained for Lithonia granite.

Sieve No.	A*	B	C	D*	E	F	G*	H	I
	Percent Passing, (%)								
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	75.7	74.3	77.0	81.2	80.0	82.2	86.1	86.2	88.1
3/8 in	56.0	56.9	56.2	68.3	67.8	68.5	75.7	76.0	76.1
No. 4	30.6	30.8	31.9	49.3	48.7	49.6	63.1	63.1	63.3
No. 8	20.5	20.7	20.6	35.0	34.8	35.4	50.9	50.9	50.7
No. 16	16.8	16.6	16.6	25.3	24.9	25.4	40.6	40.0	40.0
No. 30	12.5	12.6	12.6	17.8	17.5	18.1	31.4	30.8	30.9
No. 50	8.2	10.3	12.3	10.8	13.0	15.8	18.9	20.8	23.3
No. 100	5.0	8.8	12.3	5.9	9.7	13.9	9.7	13.4	17.4
No. 200	2.2	7.2	12.0	2.6	7.3	12.4	2.2	7.5	12.9

* Gradations with target values of zero for the minus No. 200 - results before aggregate stockpiles were washed.

1 in = 25.4 mm

Table 26. Actual gradations obtained for Watsonville granite.

Sieve No.	Gradation A*	B	C	D*	E	F	G*	H	I
	Percent Passing, (%)								
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	72.6	76.8	75.6	80.7	80.3	81.6	85.1	85.2	85.5
3/8 in	56.5	55.5	56.1	68.2	68.2	66.5	76.4	74.1	75.8
No. 4	30.2	31.6	31.9	48.9	51.1	48.2	62.5	60.1	63.5
No. 8	22.1	21.1	21.3	37.1	35.8	34.9	52.6	48.2	51.4
No. 16	17.2	17.1	17.5	26.2	24.9	26.0	41.0	37.3	39.7
No. 30	13.1	13.3	13.9	18.7	17.3	19.1	31.8	27.4	30.2
No. 50	8.5	11.0	13.3	11.4	12.6	16.7	17.1	19.5	22.9
No. 100	5.3	9.8	12.9	6.0	9.0	15.1	10.5	11.5	16.8
No. 200	1.6	7.1	12.2	1.9	6.5	13.0	2.1	6.8	12.7

* Gradations with target values of zero for the minus No. 200 - results before aggregate stockpiles were washed.

1 in = 25.4 mm

stacks, performed the analyses over a period of time, it was assumed that the test variation should fall between the precision for the single operator and between laboratories. An example of how this was used is:

> The target gradation for the No. 50 (300 μm) sieve for gradation "A" was 7.0 percent. A sieve analysis of the batched Watsonville (table 20) showed that 8.5 percent passing was obtained. The ASTM C136 precision statement indicates that, for between 3 and 10 percent of the material between consecutive sieves, the difference between two test results is 1.2 and 1.6 for within and between laboratory, respectively. Therefore, 1.5 (the difference between 7.0 and 8.5) exceeds the within-laboratory precision but is less than the between-laboratory precision.

It should be noted that the Lithonia samples (table 25), supposedly blended with no minus No. 200 (75 μm), still indicated around 2 to 2.5 percent of minus No. 200 (75 μm) was present. Based on these results, the corresponding gradations for the Watsonville aggregate (table 26) were washed, then batched and the gradation determined. It can be seen from table 26 that there was some improvement. However, some minus No. 200 (75 μm) material was still likely to be present. Most probably this is due to aggregate degradation during curing and handling, and the inability of a bulk aggregate laboratory washing operation to remove all traces of minus No. 200 (75 μm) materials. For these reasons, 2 percent or less of minus No. 200 (75 μm) was assumed to be the best that could be practically and economically achieved.

Lime

A type N normally hydrated lime supplied by Chemstar Lime Co. was used for this research program. This classification of lime is typically used in highway construction due to the more complete hydration of the oxides present in lime.

MIX DESIGNS

A Hveem mix design was completed for each gradation for each aggregate source (i.e., a total of 18 mix designs) using the Amoco AC-20 asphalt cement. Samples were fabricated with the Witco AR-4000 binder at the optimum asphalt content from these mix designs and the level of air voids was checked.

TESTING SEQUENCE

Samples were prepared and tested in accordance with ASTM D1560 and D1561. The only exception to either test method was that the samples were extruded after the leveling load and cooled to 77 °F (25 °C) prior to determining the resilient modulus. This modification was made because it was felt that the warm temperatures and high loads associated with determining Hveem stability could result in a slight decrease in air voids and an increase in resilient modulus. These same concerns also apply to determining the tensile strength; however, this test destroys the sample. Therefore, the Hveem stability (an essentially nondestructive test) was determined before the tensile strength.

The following sequence for sample preparation and testing was used:

1. Mixing, compaction [20 blows at 250 psi (1720 KPa) followed by 150 blows at 500 psi (3450 kPA)], leveling load [12,600 lb (5,720 kg)], and extrusion of samples.

2. Samples were then cooled to 77 °F (25 °C), and the sample height, resilient modulus (ASTM D4123), and bulk specific gravity (ASTM D2726) were determined.

3. Samples were placed in a 140 °F (60 °C) oven for 2 hours, after which Hveem stability was determined.

4. Samples were then cooled to 77 °F (25 °C), and the tensile strength was determined at a constant strain of 2 in/minute (50 mm/minute).

5. Theoretical maximum specific gravity was determined for one loose mixed sample at the projected optimum asphalt cement content. This theoretical maximum specific gravity was used to calculate the theoretical maximum specific gravity for remaining asphalt contents.

MIX DESIGN RESULTS

The results from mixes prepared with the Amoco AC-20 are shown in tables 27 and 28 and graphically in figures 39 through 44. The optimum asphalt content for each gradation was selected based solely on 4 percent air voids (table 29). The 4-percent air void criterion was chosen in order to produce a tighter range of air voids for samples prepared with like compactive effort for the main test matrix cells.

The applicability of the selected asphalt cement content for mixes with the same gradation but using the Witco AR-4000 were randomly checked. Again, the 4-percent air void criteria was used in order to determine if the asphalt content would change because of the change in binder. These test results are shown in table 30. It can be seen that while there is some variation around 4 percent, this variation is with ±0.5 percent air voids (i.e., typical range of air voids within a set of three samples of the same material).

Since no change in optimum asphalt content was needed for any of the randomly checked mixtures prepared with the Witco AR-4000, the remaining optimum asphalt contents for these mixtures were the same as those chosen for mixtures prepared with the Amoco AC-20 for corresponding gradations.

ADDITIONAL EVALUATION OF MIX DESIGN TEST RESULTS

While examining the mix design test results, a trend was observed between VMA, the gradation, and the sensitivity of resilient modulus and tensile strength. A preliminary statistical analysis used both single and multiple linear regression models to estimate the significance of this observations. Both aggregate data bases were combined for this analysis.

Table 27. Results of final mix designs, Lithonia granite(stripper), used for the selection of optimum asphalt contents.

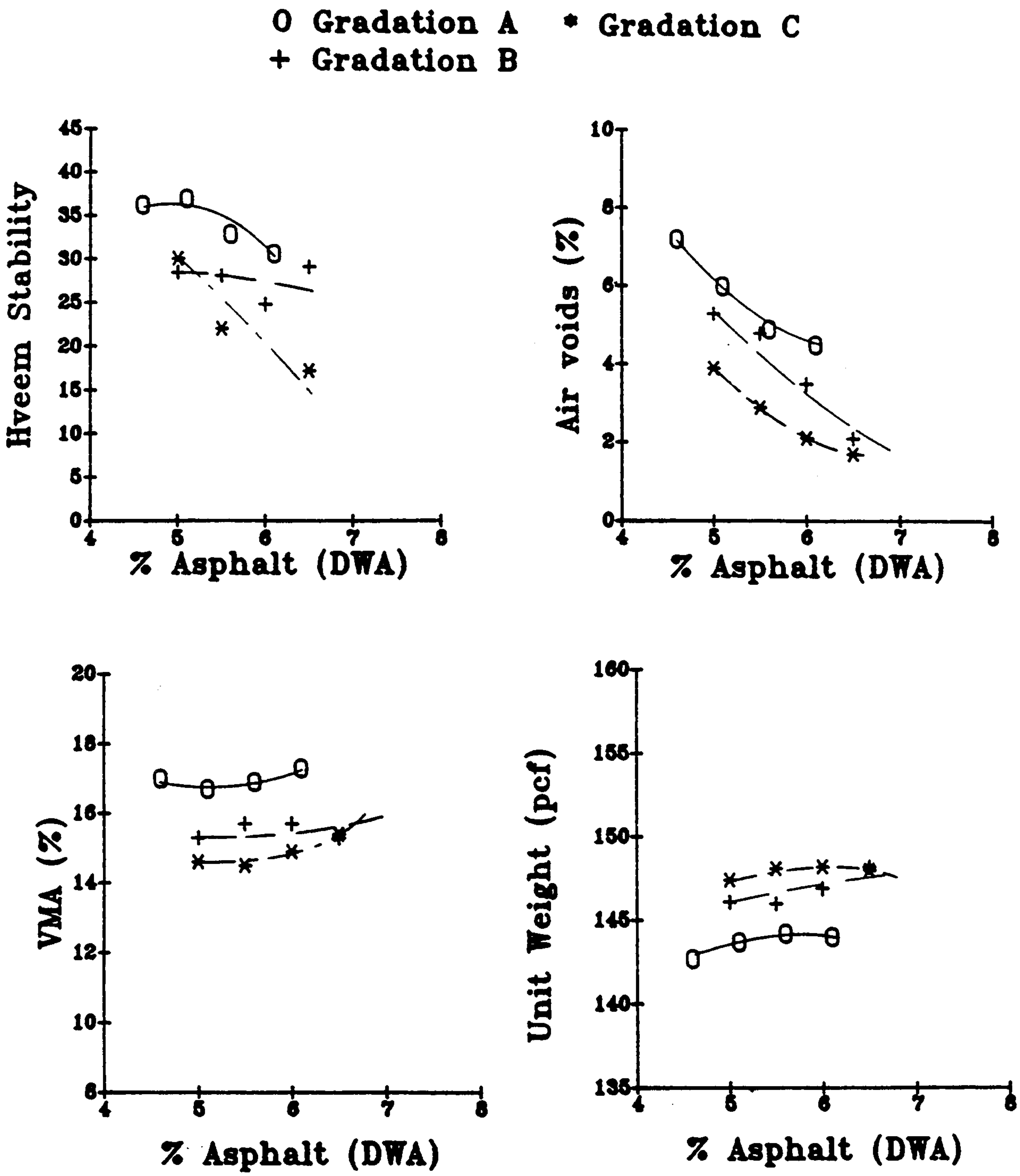
Gradation	Percent Asphalt	Hveem Stability	Percent Voids	VMA	Mr (ksi)	Splitting Tension 77 °F (psi)
A	4.6	36.2	7.2	17.0	127	56.9
A	5.1	36.9	6.0	16.7	178	70.3
A	5.6	32.8	4.9	16.9	180	75.3
A	6.1	30.6	4.5	17.3	145	67.5
B	5.0	28.4	5.3	15.3	249	82.1
B	5.5	28.0	4.8	15.7	167	69.2
B	6.0	24.8	3.5	15.7	184	70.1
B	6.5	29.1	2.1	15.3	223	79.1
C	5.0	30.0	3.9	14.6	245	95.2
C	5.5	22.0	2.9	14.5	183	94.6
C	6.0	No Data	2.1	14.9	178	85.4
C	6.5	17.2	1.7	15.4	167	76.0
D	4.6	27.4	8.1	17.5	144	68.0
D	5.1	22.0	6.2	16.8	188	80.9
D	5.6	31.2	5.8	17.3	150	83.0
D	6.1	16.4	3.4	16.3	135	72.0
E	4.5	28.1	4.5	15.1	279	175.5
E	5.0	26.6	2.6	14.5	321	166.3
E	5.5	27.6	2.6	15.4	228	152.7
E	6.0	21.7	1.9	15.9	216	152.9
F	4.0	34.3	7.6	11.1	190	94.4
F	5.0	20.0	3.2	13.3	236	110.4
F	5.5	17.1	2.1	13.3	230	91.8
F	6.0	5.0	1.9	14.2	148	84.0
F	6.5	4.0	1.6	14.8	140	73.1
G	6.0	22.1	6.1	19.0	134	113.0
G	6.5	20.4	5.5	19.3	125	117.1
G	7.0	24.8	3.8	18.7	140	114.9
G	7.5	25.6	2.6	18.6	152	115.9
G	8.0	23.2	1.6	18.8	111	108.3
H	5.0	28.9	6.1	16.6	175	126.4
H	5.5	29.0	4.7	16.2	211	146.4
H	6.0	24.1	2.9	15.7	309	192.4
H	6.5	22.8	1.5	15.6	225	177.8
H	7.0	15.8	1.1	16.2	198	160.1
I	5.0	21.5	4.0	14.9	348	134.0
I	5.5	22.9	1.8	13.8	325	130.7
I	6.0	11.0	1.2	14.4	194	103.6
I	6.5	7.5	1.3	15.3	164	93.0

1 ksi = 6.89 MPa
1 psi = 6.89 kPa
°C = 5(°F-32)/9

Table 28. Results of final mix designs, Watsonville granite(nonstripper), used for the selection of optimum asphalt contents.

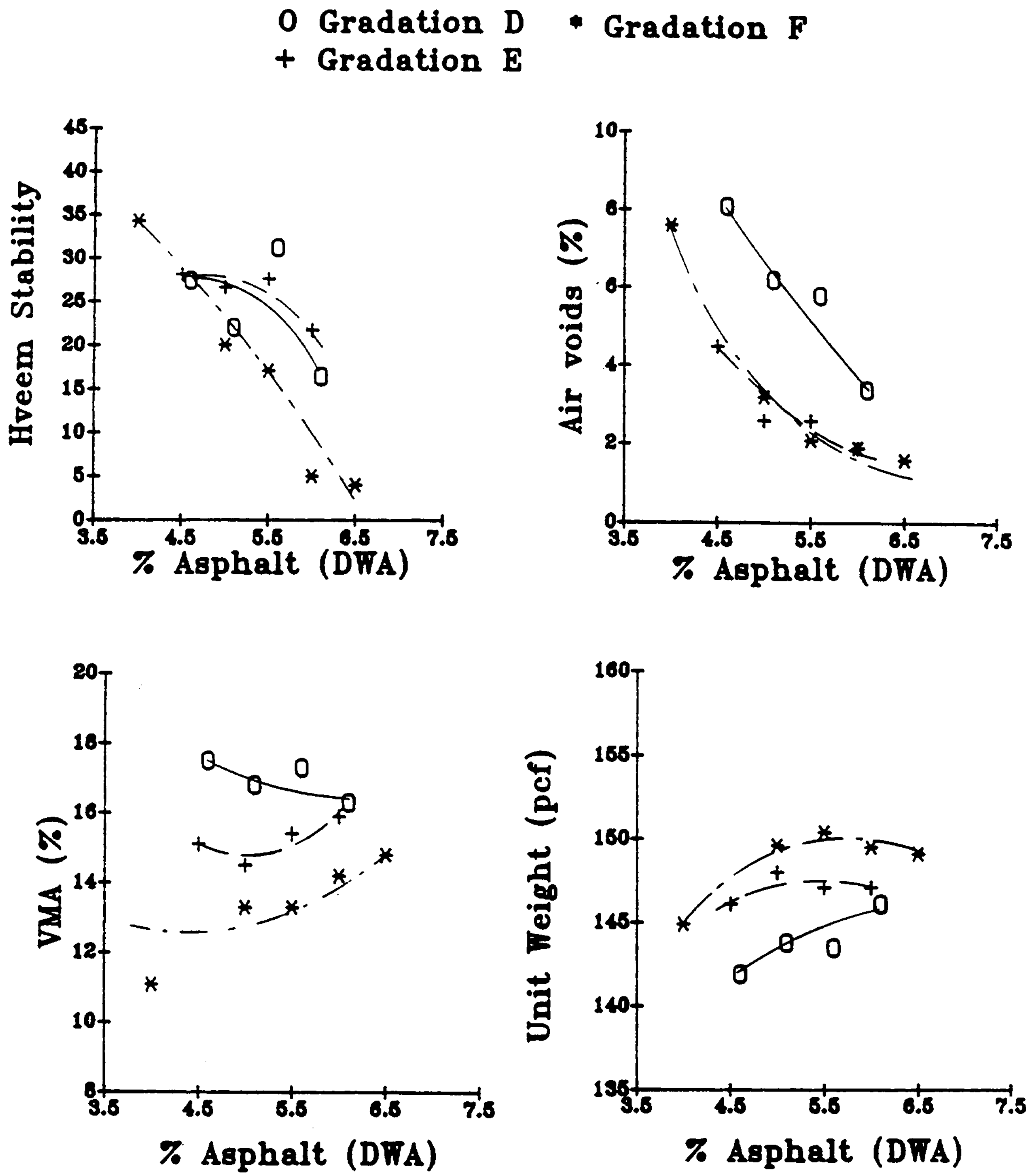
Gradation	Percent Asphalt	Hveem Stability	Percent Voids	VMA	Mr (ksi)	Splitting Tension 77 °F (psi)
A	5.0	34.5	7.7	13.6	207	122.9
A	6.0	28.6	4.7	14.1	223	114.6
A	6.5	36.2	3.8	14.3	249	127.4
A	7.0	32.5	1.6	13.4	246	119.2
B	5.0	28.0	6.8	13.8	192	59.2
B	5.9	26.8	4.9	13.8	232	61.2
B	6.0	24.2	3.4	12.7	136	54.0
B	6.5	27.0	3.8	14.0	188	64.9
C	5.0	26.0	4.8	12.5	235	79.2
C	5.5	24.0	5.0	13.6	192	68.5
C	6.0	25.5	3.0	12.9	199	66.1
C	6.5	28.2	1.8	12.8	158	61.3
D	4.7	29.5	6.6	12.7	186	83.9
D	5.3	29.8	5.7	13.1	179	77.1
D	5.8	32.0	4.1	12.7	188	92.4
D	6.3	32.9	3.7	13.2	216	86.9
E	4.0	36.5	6.8	11.0	276	140.0
E	4.5	29.8	5.6	10.7	354	156.4
E	5.0	31.6	3.5	10.5	331	162.3
E	5.5	30.5	2.0	10.1	330	170.4
F	4.0	31.7	7.0	10.6	230	86.6
F	5.0	18.1	1.5	8.7	284	103.2
F	5.5	10.2	0.8	9.0	328	95.3
F	6.0	6.7	0.2	9.7	247	90.7
G	6.0	27.6	6.9	16.1	203	139.8
G	6.5	30.2	6.0	16.3	211	156.3
G	7.0	30.1	5.8	17.1	236	149.0
G	7.5	33.1	3.7	16.4	291	151.2
G	8.0	27.9	2.4	16.2	230	154.7
H	5.0	36.4	6.9	12.9	473	146.3
H	5.5	24.7	6.4	13.4	455	138.0
H	6.0	29.6	4.9	13.1	424	140.4
H	6.5	11.3	3.9	13.1	251	122.5
I	5.0	38.0	4.7	10.5	433	135.5
I	5.5	20.4	2.5	9.5	300	125.1
I	6.0	10.0	2.0	10.2	267	106.3
I	6.5	6.0	1.4	10.6	251	108.8

1 ksi = 6.89 MPa
1 psi = 6.89 kPa
°C = 5(°F-32)/9



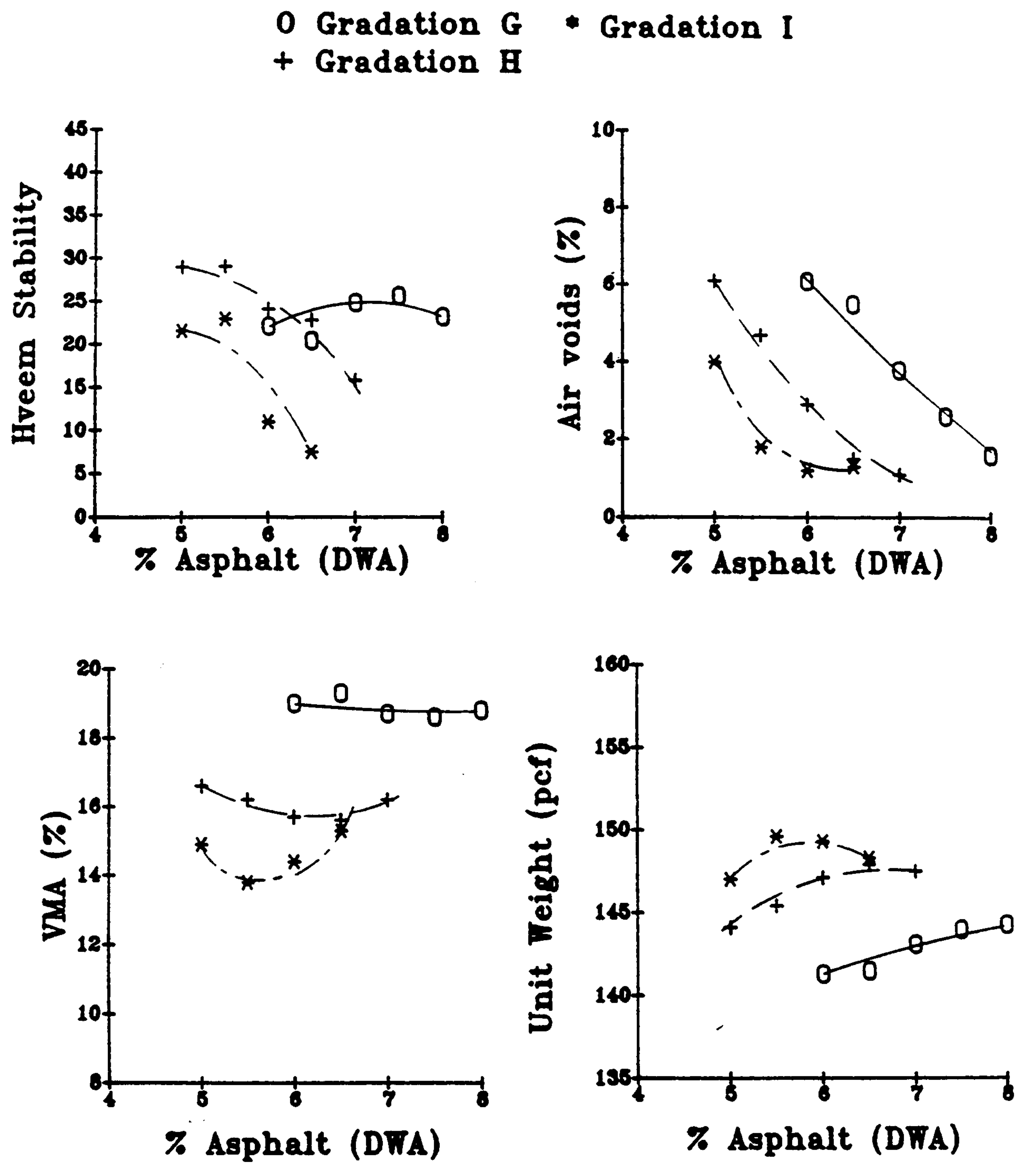
1 pcf = 16.0 kg/m^3

Figure 39. Mix designs for Lithonia granite, gradations a, b & c.



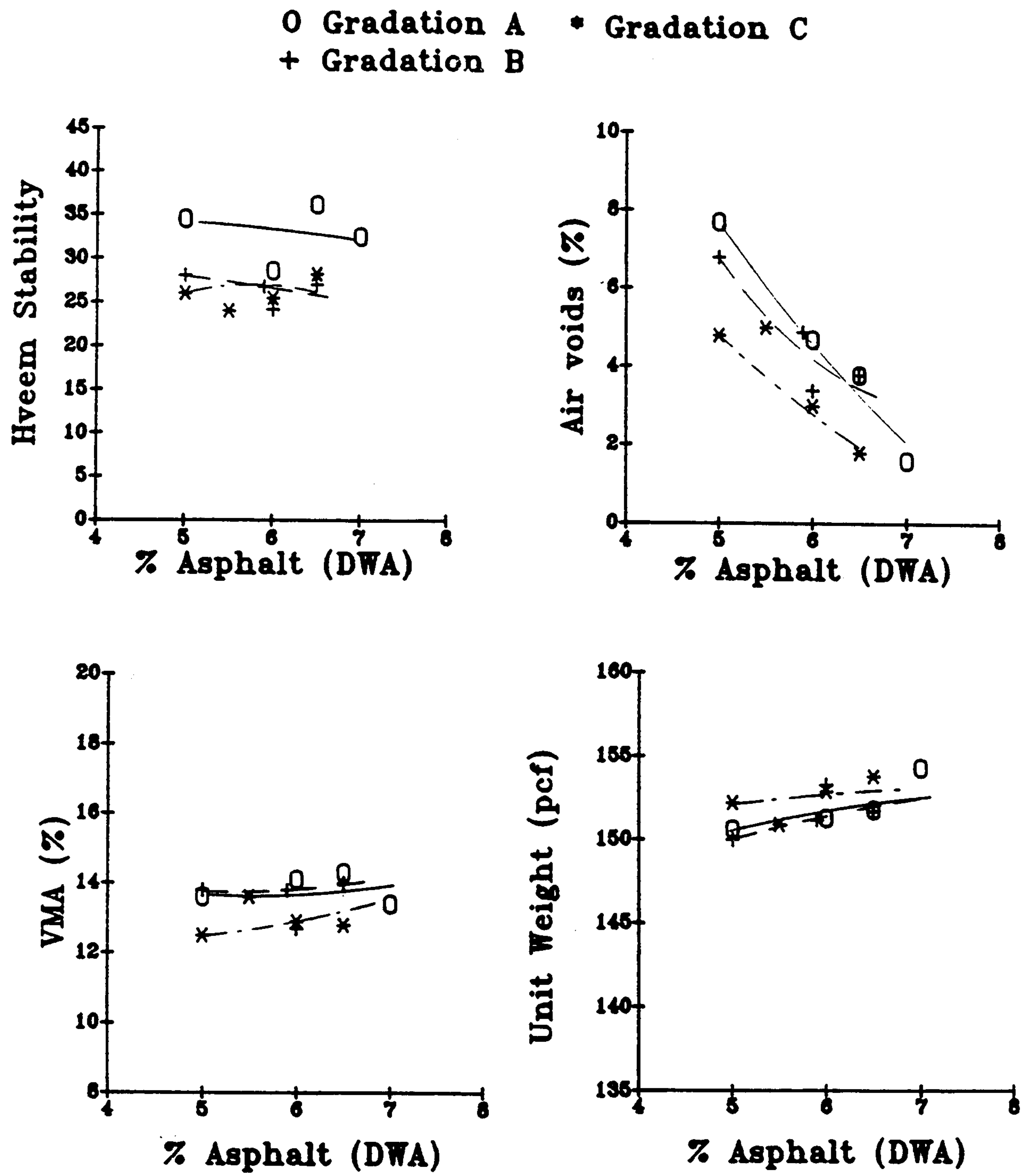
1 pcf = 16.0 kg/m^3

Figure 40. Mix designs for Lithonia granite, gradations d, e & f.



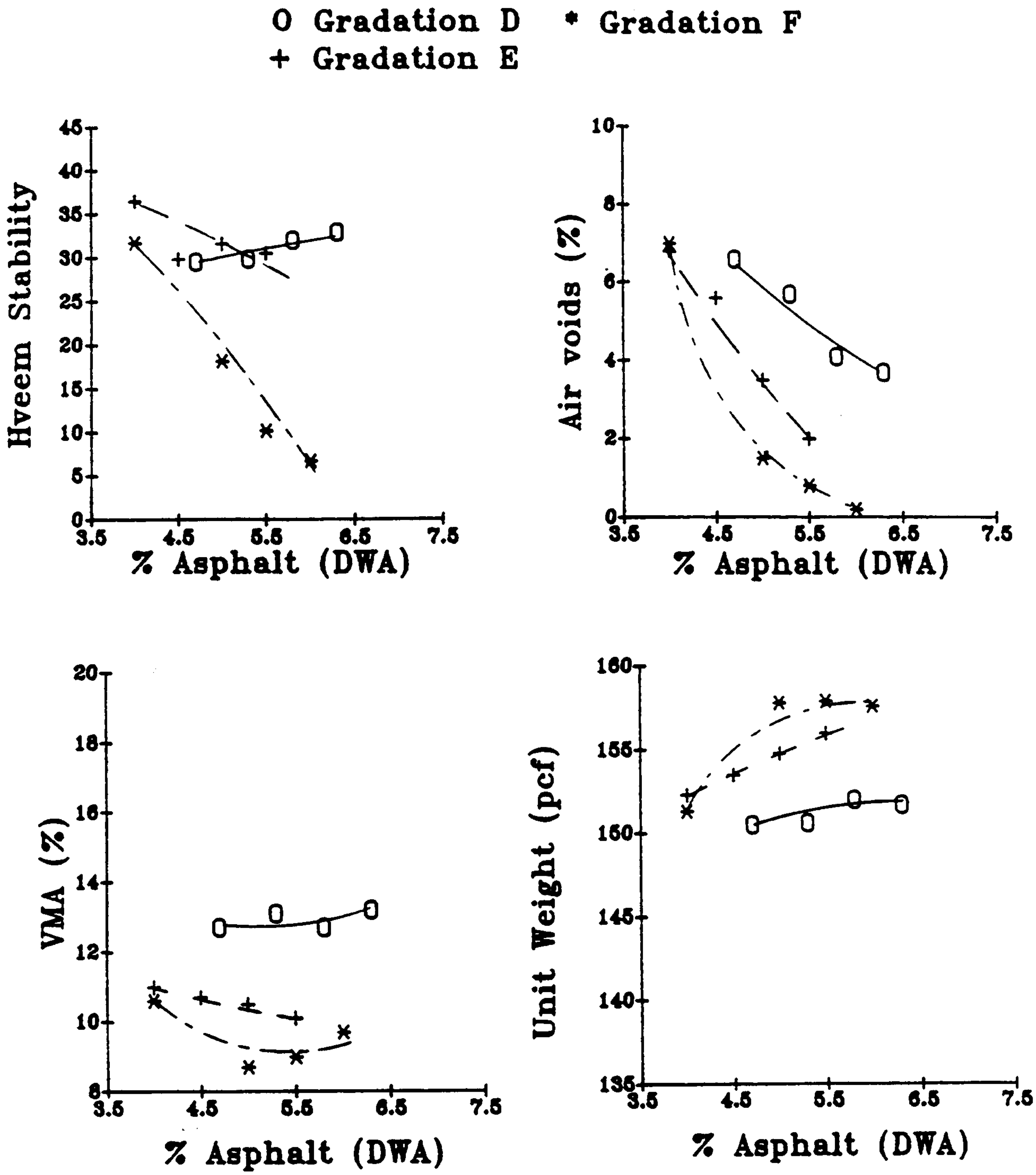
1 pcf = 16.0 kg/m^3

Figure 41. Mix designs for Lithonia granite, gradations g, h & i.



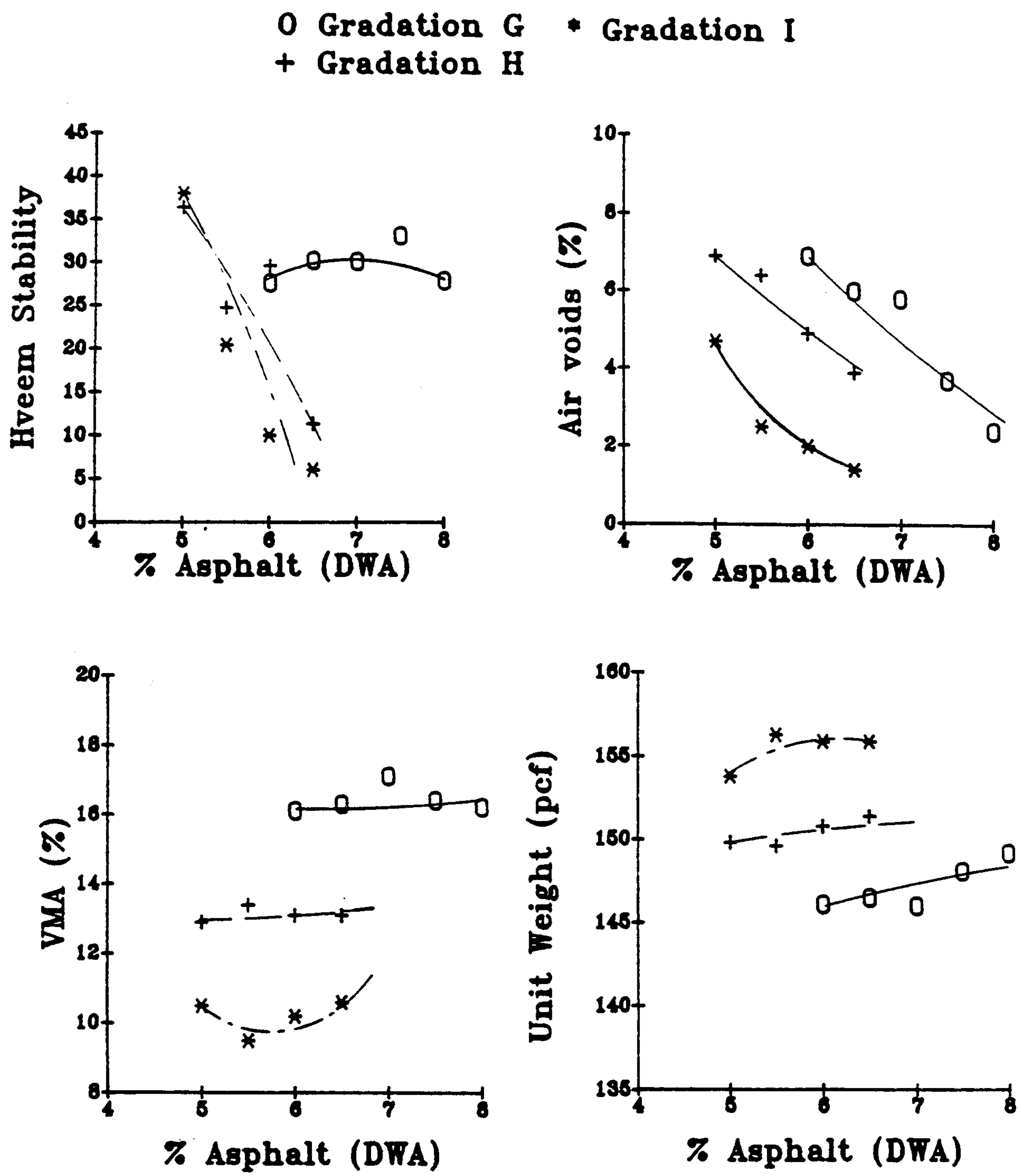
1 pcf = 16.0 kg/m^3

Figure 42. Mix designs for Watsonville granite, gradations a, b & c.



1 pcf = 16.0 kg/m^3

Figure 43. Mix designs for Watsonville granite, gradations d, e & f.



1 pcf = 16.0 kg/m^3

Figure 44. Mix designs for Watsonville granite, gradations g, h & i.

Table 29. Optimum asphalt cement content based upon 4 percent air voids for mixtures prepared with Amoco AC-20.

Aggregate Source	Gradation								
	A	B	C	D	E	F	G	H	I
	Asphalt Cement Content, % (Dry Weight of Aggregate)								
Lithonia Granite	6.6	5.6	4.9	5.9	4.7	4.8	6.9	5.6	5.0
Watsonville Granite	6.2	6.1	5.3	6.0	4.8	4.3	7.4	6.5	5.2

Table 30. Random check of air voids for mixtures prepared with the Witco AR-4000 at the Amoco AC-20 optimum asphalt content.

Asphalt Cement	Gradation								
	A	B	C	D	E	F	G	H	I
	Air Voids								
Lithonia Aggregate									
Amoco AC-20	4.5	4.4	3.9	3.6	4.2	4.3	3.8	--	4.0
Witco AR-4000	4.5	4.3	--	--	3.5	--	--	--	3.5
Watsonville Aggregate									
Amoco AC-20	4.3	3.7	4.5	4.3	3.5	4.0	4.2	4.1	4.0
Witco AR-4000	3.9	4.3	--	--	3.6	3.5	--	--	3.6

Selection of Input for Variables: The independent variables selected were the VMA at the optimum asphalt content (i.e., 4-percent air voids) and the fineness modulus. The fineness modulus (i.e., the summation of the cumulative percents retained from a complete sieve analysis) was selected as a one-number representation of variations in gradation.

Dependent variables selected were the resilient modulus and tensile strength. Both of these values were also selected at 4-percent air voids. Both single and multiple linear regression models were developed for all combinations of dependent-independent variables. The results from this preliminary analysis are shown in table 31.

Analysis-Estimating Resilient Modulus: The multiple regression model using VMA and the fineness modulus to estimate resilient modulus explain approximately 55 percent of the data scatter (i.e., r^2=.55). Single regression models result in substantially lower correlations of approximately 28 percent for each independent variable.

While the multiple linear regression model looks promising, it was developed for only one grade of asphalt cement. Therefore, it is suggested that a third independent variable representing asphalt cement viscosity should be added in future model development.

Analysis-Estimating Tensile Strength: The multiple regression model using VMA and the fineness modulus to estimate tensile strength explain approximately 38 percent of the data scatter. However, an examination of the single regression models indicated that approximately this same level of correlation is defined by the fineness modulus alone. There was virtually no correlation between VMA and tensile strength.

CONCLUSION

The mix design tests were used to identify the optimum asphalt contents to be used for each aggregate and asphalt cement source for the remainder of the testing program. Plus or minus 0.75 percent of asphalt from each optimum would be used to define test matrix cells identified as "high" and "low" binders, respectively. The preliminary statistical analysis of the mix design data indicated that there should be a strong correlation between resilient modulus and both VMA and fineness modulus. It also indicates a moderate correlation between tensile strength and fineness modulus.

Table 31. Results for preliminary regression analysis of mix design data.

Independent Variable	Equation
Multiple Linear Regression Models	
Resilient Modulus (ksi)	= 862.18 - 16.573(VMA) - 65.23(Fineness Modulus) (r^2 = 0.549)
Tensile Strength (psi)	= 329.76 - 0.797(VMA) - 34.654(Fineness Modulus) (r^2 = 0.383)
Single Linear Regression Models	
Resilient Modulus (ksi)	= 476.08 - 16.874(VMA) (r^2 = 0.284)
Resilient Modulus (ksi)	= 635.78 - 66.467(Fineness Modulus) (r^2 = 0.275)
Tensile Strength (psi)	= 124.66 - 0.957(VMA) (r^2 = 0.005)
Tensile Strength (psi)	= 318.87 - 34.714(Fineness Modulus) (r^2 = 0.379)

1 ksi = 6.89 MPa
1 psi = 6.89 kPa

APPENDIX C
TEST PROCEDURES AND DATA SUMMARIES

INTRODUCTION

The experiment for the laboratory study of this project is described in chapter 5. The study was conducted in three separate parts. The main factorial experiment consisted of a study of the effects of different materials and construction variables on resilient modulus and tensile strength measured at different temperatures, after aging and after moisture conditioning. Two smaller experiments were conducted on replicate samples to determine creep and fatigue resistance before and after moisture conditioning.

The testing sequence followed in the main factorial experiment is shown in figure 45.

SPECIMEN PREPARATION

Specimens were prepared in batches using the procedure described in appendix B, except that aggregate gradations, asphalt contents and other variables were modified in accordance with the experimental plan described in chapter 5. A random plan for testing was established to remove bias as much as possible. Compaction was accomplished using a kneading compactor in accordance with ASTM Method D1561, Preparation of Bituminous Mixtures by California Kneading Compactor. The number of tamps and the foot pressure of the compactor were adjusted to produce samples with air voids between 1 and 5 percent, between 5 and 8 percent, and between 8 and 12 percent.

Cylindrical specimens 2.5 in (63 mm) high and 4.0 in (102 mm) in diameter were tested using the diametrical apparatus described in ASTM Method D4123, Indirect Tension Test for Resilient Modulus of Bituminous Mixtures, for all tests except creep. Creep tests were performed on 4.0-in (102 mm) diameter specimens approximately 8 in (203 mm) high.

Theoretical maximum specific gravity was determined on samples of loose mix using the procedure in ASTM Method D2041, Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures.

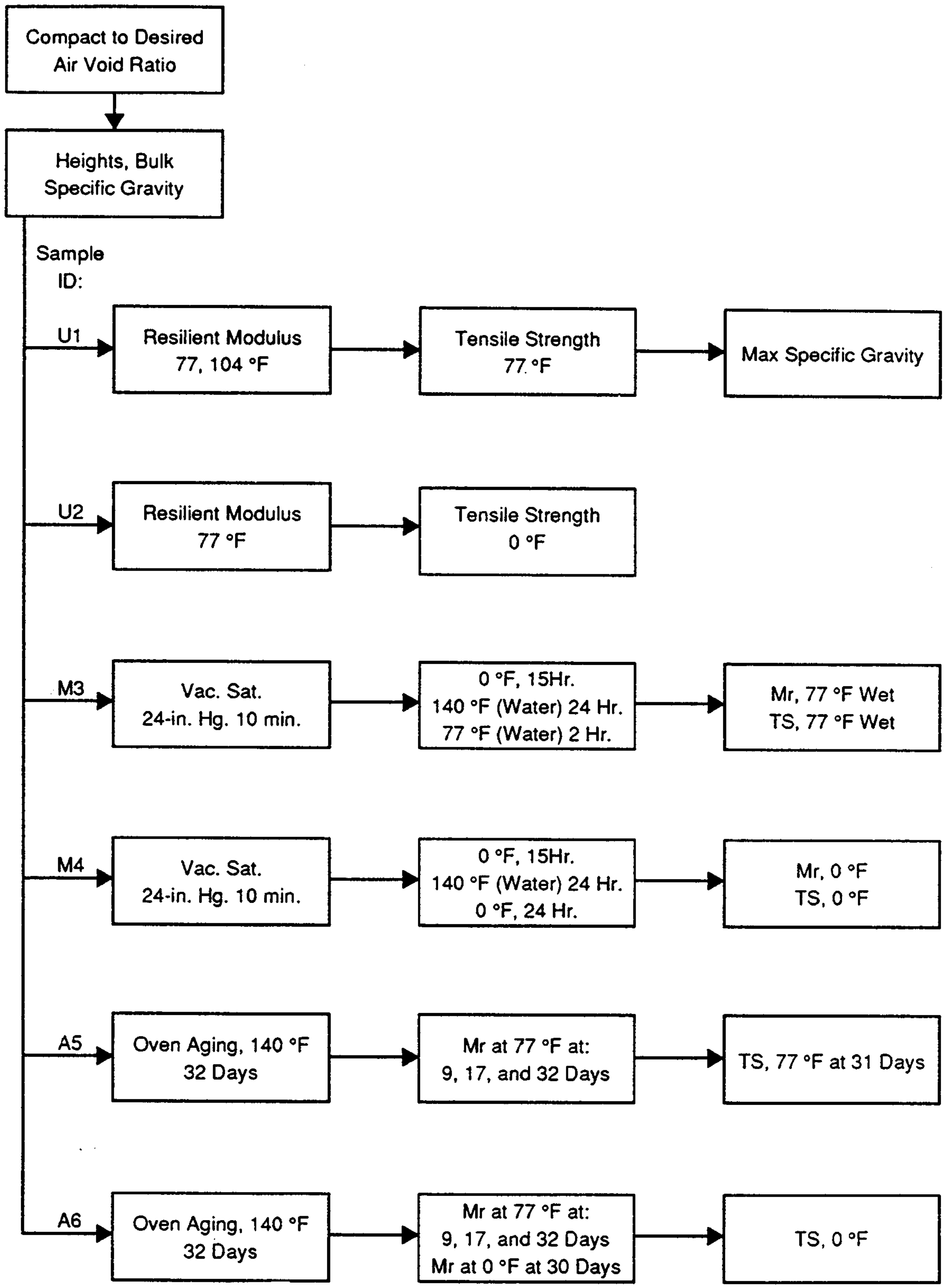
RESILIENT MODULUS AND TENSILE STRENGTH TESTING

Testing Sequence

The testing sequence for all MR and TS testing, both before and after aging or moisture conditioning, is shown in figure 45.

Test Apparatus

A Retsina Mark IV testing machine was used to determine resilient modulus and tensile strength. This equipment applies a 0.1 s load once every 3 s (0.33 Hz). The M_r test was performed in accordance with ASTM D4123, Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. When the resilient modulus was determined at temperatures other than 77 °F



°C = 5(°F-32)/9
1 in = 25.4 mm

Figure 45. Testing sequences for main factorial experiment.

(25 °C), testing was completed within 4 min of removing the sample from the environmental chamber.

The tensile strength at 77 °F (25 °C) was determined at a constant strain rate of 2 in (50 mm) per minute. The tensile strength at 0 °F (-18 °C) was determined at a constant strain rate of 0.1 in (2.5 mm) per minute.

Moisture Conditioning

The moisture conditioning procedure was a modified version of the Lottman accelerated conditioning procedure. In this procedure the specimen is vacuum saturated at 24 in (610 mm) of mercury for 10 minutes, wrapped in plastic film, placed in a sealable plastic bag with 10 ml of water for each sample, and cooled at 0 °F (-18 °C) for a minimum of 15 hours. After this time, the samples were unwrapped and placed in a 140 °F (60 °C) water bath for 24 hours (± 1 hour), then moved to a 77 °F (25 °C) water bath for 2 hours (± 0.5 hour); resilient modulus [(77 °F (25 °C), wet] and tensile strength [77 °F (25 °C), wet] were then determined.

Aging

Samples were compacted, and the heights, bulk specific gravities, and original resilient modulus at 77 °F (25 °C) were determined. Samples were then stored in a 140 °F (60 °C) oven for 32 days. The samples were removed from the oven at 9 and 17 days and cooled at 77 °F (25 °C); after cooling, the resilient modulus was determined in order to establish the increase in mixture stiffness with time. Samples were immediately returned to the 140 °F (60 °C) oven after this intermediate testing.

Other Testing

Other conventional testing used in this experiment included:

- Bulk specific gravity (ASTM D2726).
- Theoretical maximum specific gravity (ASTM D2041).

Test Data

Test data obtained for the resilient modulus and indirect tensile strength are summarized in table 32.

CREEP TESTING

The creep testing procedure utilized a 4-in (102-mm) diameter by 8-in (203-mm) high specimen subjected to an axial seating (or pre-conditioning) 1-Hz sine wave load, from 0 to 20 psi (0 to 138 kPa), for 1 min (60 cycles), followed by a 10-s rest period. After preconditioning a static load of 20 psi (138 kPa) was applied for 1 h. At the end of this time all loading was removed, and the sample allowed to rebound for 1 h. The strain remaining at the end of this time was reported as the permanent strain.

Table 32. Resilient modulus and tensile strength test data.

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL ANALYSIS.

Random Cell No.	Group Cell No.	AC %	Compaction Level		AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	Res. Mod. (77 F, 1 Day) AIR VOIDS	Res. Mod. (77 F, 1 Day) MR (ksi)	Ten. Str. (77 F, 1Day) AIR VOIDS	Ten. Str. (77 F, 1Day) TS (psi)	Aged MR Ratio (77 F) AIR VOIDS	Aged MR Ratio (77 F) MR 32day / MR 1day	Aged TS Ratio (77 F) AIR VOIDS	Aged TS Ratio (77 F) TS 32day / TS 1day	TS/MR Ratio (77F, 1Day) AIR VOIDS	TS/MR Ratio (77F, 1Day) TS/MR
1	303	0.75	high	1	0	No	13.0	2.1	12.60	High	3.8	117.8	2.7	70.9	2.8		2.8		2.7	0.496
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	3.0	401.2	2.9	171.1	2.3	1.301	2.6	1.701	2.9	0.450
3	408	-0.75	med	0	1	Yes	13.0	12.5	15.62	High	8.7	231.6	9.5	47.8	9.5	2.925	9.5	2.877	9.5	0.337
4	407	0.75	low	-1	1	Yes	13.0	7.1	18.10	High	9.2	87.3	9.1	47.5	8.5		8.8		9.1	0.470
5	209	0.00	high	1	1	No	13.0	12.5	16.95	Low	13.0	479.3	13.1	259.3	11.3	2.935	12.2	1.038	13.1	0.547
6	104	0.75	high	1	0	Yes	13.0	2.1	18.19	Low	2.4	117.3	3.0	115.6	2.2	1.544	2.6	0.806	3.0	1.145
7	120	0.75	low	-1	0	No	30.4	2.1	28.47	Low	14.7	18.2	15.0	34.7	15.2	4.000	15.1	1.504	15.0	1.577
8	220	0.75	high	1	1	No	30.4	2.1	20.45	Low	6.3	235.2	6.1	252.1	5.9	1.656	6.0	0.998	6.1	1.141
9	325	-0.75	high	1	0	Yes	30.4	12.5	13.95	High	9.3	292.3	9.3	106.6	9.0	2.285	9.2	1.327	9.3	0.363
10	110	0.75	low	-1	0	No	13.0	12.5	20.44	Low	9.2	32.0	9.4	32.5	8.5		9.0		9.4	0.878
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	4.5	306.5	5.2	155.1	4.3	1.645	4.8	1.749	5.2	0.669
12	412	0.00	med	0	1	No	18.1	2.1	17.40	High	9.4	396.2	10.0	114.4	9.6	1.510	9.8	1.495	10.0	0.413
13	401	-0.75	high	1	1	Yes	13.0	2.1	24.36	High	17.5	587.7	17.6	215.0	18.1	1.950	17.9	1.040	17.6	0.327
14	114	-0.75	low	-1	0	Yes	18.1	12.5	23.27	Low	14.7	38.2	14.9	15.7	14.8	2.743	14.9	2.045	14.9	0.436
15	124	-0.75	low	-1	0	No	30.4	12.5	12.37	Low	3.0	21.2	2.7	16.3	1.9	4.263	2.3	2.245	2.7	0.627
16	307	-0.75	high	1	0	No	13.0	12.5	11.09	High	3.8	214.0	3.9	101.8	0.0		3.9		3.9	0.497
17	223	-0.75	med	0	1	Yes	30.4	12.5	19.52	Low	10.4	253.3	10.1	115.5	10.8	3.453	10.5	1.107	10.1	0.402
18	105	0.75	low	-1	0	No	13.0	7.1	20.89	Low	9.5	312.5	9.0	36.6	9.5		9.3		9.0	0.117
19	427	0.75	med	0	1	No	30.4	12.0	14.80	High	5.6	537.0	5.9	173.7	5.3	1.939	5.6	1.244	5.9	0.258
20	405	-0.75	low	-1	1	No	13.0	7.1	19.15	High	11.1	99.3	11.6	45.1	10.2		10.9		11.6	0.385
21	211	0.75	low	-1	1	Yes	13.0	12.5	20.94	Low	9.8	137.2	9.7	64.0	9.6	2.483	9.7	1.384	9.7	0.405
22	402	-0.75	med	0	1	No	13.0	2.1	16.09	High	9.1	207.0	8.4	87.0	8.1		8.3		8.4	0.414
23	417	-0.75	low	-1	1	No	30.4	2.1	24.64	High	16.1	93.2	15.5	47.4	16.0	2.060	15.7	1.570	15.5	0.484
24	226	0.75	low	-1	1	No	30.4	12.5	24.06	Low	13.2	107.7	13.5	58.2	12.8	3.548	13.2	1.845	13.5	0.529
25	312	0.00	high	1	0	Yes	18.1	2.1	13.10	High	3.1	310.2	3.5	130.5	2.8	1.652	3.2	1.006	3.5	0.353
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	7.7	588.8	7.8	228.7	7.3	2.053	7.6	1.268	7.8	0.403
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	10.0	219.7	9.3	84.5	10.2	3.024	9.8	1.142	9.3	0.384
28	107	-0.75	high	1	0	Yes	13.0	12.5	14.22	Low	6.1	244.5	5.7	126.3	7.0	2.878	6.4	0.979	5.7	0.473
29	302	-0.75	low	-1	0	No	13.0	2.1	19.15	High	11.2	29.3	11.3	17.3	10.8		11.1		11.3	0.618
30	326	-0.75	low	-1	0	No	30.4	12.5	20.80	High	16.8	74.7	17.1	23.0	17.1	3.619	17.1	1.983	17.1	0.377
31	125	0.00	med	0	0	No	30.4	12.5	16.72	Low	7.3	172.8	6.6	109.6	7.3	2.701	7.0	1.216	6.6	0.580
32	118	-0.75	med	0	0	Yes	30.4	2.1	21.81	Low	9.6	92.7	9.7	69.8	9.4	2.318	9.6	1.458	9.7	0.727
33	414	-0.75	low	-1	1	Yes	18.1	12.5	20.69	High	18.5	106.7	18.4	31.6	18.8		18.6		18.4	0.322
34	119	0.75	high	1	0	Yes	30.4	2.1	18.55	Low	2.2	139.0	2.5	120.7	2.5	1.681	2.5	0.993	2.5	0.862
35	310	0.75	low	-1	0	No	13.0	12.5	18.02	High	8.7	38.5	8.9	29.5	8.5		8.7		8.9	0.738
36	212	-0.75	low	-1	1	No	18.1	2.1	23.96	Low	14.4	79.8	14.3	49.1	14.9	3.149	14.6	1.293	14.3	0.614
37	221	0.75	low	-1	1	Yes	30.4	2.1	25.93	Low	11.0	104.2	11.2	60.6	11.0	3.674	11.1	1.837	11.2	0.566
38	216	0.75	high	1	1	Yes	18.1	7.1	14.25	Low	1.6	557.8	2.2	238.7	1.5	1.449	1.9	1.028	2.2	0.432
39	117	-0.75	high	1	0	No	30.4	2.1	19.49	Low	7.2	100.2	6.7	96.3	10.0	2.918	8.4	1.083	6.7	0.852
40	208	-0.75	low	-1	1	No	13.0	12.5	19.28	Low	10.9	121.5	10.9	39.7	11.4	5.026	11.2	0.993	10.9	0.351
41	308	0.00	low	-1	0	No	13.0	12.5	16.59	High	9.3	46.7	9.4	25.4	9.4	5.480	9.4	2.311	9.4	0.620
42	112	0.00	med	0	0	No	18.1	2.1	18.55	Low	7.4	116.2	6.8	63.1	7.3	2.071	7.1	1.534	6.8	0.485
43	415	-0.75	high	1	1	No	18.1	12.5	9.76	High	5.3	981.7	5.3	184.0	6.3	2.607	5.8	1.388	5.3	0.235
44	201	-0.75	low	-1	1	Yes	13.0	2.1	22.43	Low	9.9	114.7	10.8	48.0	9.3	3.176	10.1	0.983	10.8	0.410
45	301	-0.75	low	-1	0	Yes	13.0	2.1	18.65	High	10.5	40.5	11.2	24.0	10.1	9.705	10.7	2.925	11.2	0.571
46	411	0.75	high	1	1	No	13.0	12.5	10.97	High	1.9	558.0	1.8	171.5	2.6	1.536	2.2	1.227	1.8	0.397
47	102	-0.75	high	1	0	No	13.0	2.1	16.17	Low	4.5	167.5	4.1	92.3	4.2	1.270	4.2	1.024	4.1	0.519
48	319	-0.75	high	1	0	No	30.4	2.1	16.22	High	6.3	261.8	6.5	123.6	6.4	1.757	6.5	1.210	6.5	0.470
49	315	0.75	low	-1	0	Yes	18.1	2.1	23.23	High	9.7	46.2	9.7	32.5	9.5	6.653	9.6	2.665	9.7	0.813
50	215	0.00	low	-1	1	Yes	18.1	7.1	21.93	Low	12.1	175.5	12.7	61.3	12.0	6.925	12.4	2.527	12.7	0.454
51	222	-0.75	high	1	1	No	30.4	7.1	16.48	Low	6.6	867.5	6.3	302.0	6.7	1.639	6.5	0.831	6.3	0.319
52	421	0.00	high	1	1	Yes	30.4	7.1	12.29	High	3.0	813.8	2.5	240.4	3.1	2.010	2.8	1.158	2.5	0.289

Table 32. Resilient modulus and tensile strength test data (continued).

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL ANALYSIS.

Random Cell No.	Group Cell No.	AC %	Compaction Level		AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	Res. Mod. (77 F, 1 Day) AIR VOIDS	Res. Mod. (77 F, 1 Day) MR (ksi)	Ten. Str. (77 F, 1Day) AIR VOIDS	Ten. Str. (77 F, 1Day) TS (psi)	Aged MR Ratio (77 F) AIR VOIDS	Aged MR Ratio (77 F) MR 32day / MR 1day	Aged TS Ratio (77 F) AIR VOIDS	Aged TS Ratio (77 F) TS 32day / TS 1day	TS/MR Ratio (77F, 1Day) AIR VOIDS	TS/MR Ratio (77F, 1Day) TS/MR
53	313	0.00	high	1	0	No	18.1	2.1	13.75	High	5.4	243.5	4.9	103.2	5.3	2.250	5.1	1.279	4.9	0.346
54	306	-0.75	med	0	0	No	13.0	7.1	14.30	High	7.6	137.3	7.0	54.2	7.4	1.423	7.2	1.256	7.0	0.480
55	426	0.75	high	1	1	Yes	30.4	12.0	12.78	High	4.8	890.2	4.9	223.0	4.2	2.292	4.6	1.384	4.9	0.240
56	213	-0.75	med	0	1	Yes	18.1	2.1	19.32	Low	8.7	263.7	8.7	116.5	9.1		8.9		8.7	0.365
57	218	-0.75	low	-1	1	Yes	30.4	2.1	28.44	Low	14.8	110.7	16.9	42.3	14.6	3.787	15.8	2.986	16.9	0.486
58	328	0.75	low	-1	0	Yes	30.4	12.5	20.28	High	12.1	102.8	11.9	39.8	12.4	3.608	12.2	1.672	11.9	0.410
59	121	-0.75	low	-1	0	No	30.4	7.1	23.62	Low	16.8	41.2	17.0	28.1	16.8	5.750	16.9	2.584	17.0	0.669
60	304	0.75	med	0	0	Yes	13.0	2.1	15.39	High	6.4	136.3	5.9	53.5	6.6	1.250	6.3	1.376	5.9	0.374
61	321	0.75	low	-1	0	No	30.4	2.1	24.88	High	12.6	33.7	12.8	20.5	12.0	1.800	12.4	2.585	12.8	0.603
62	322	0.00	med	0	0	Yes	30.4	7.1	13.40	High	5.9	284.3	5.3	115.1	6.1	1.893	5.7	1.192	5.3	0.397
63	403	0.75	low	-1	1	Yes	13.0	2.1	18.78	High	9.4	113.8	8.8	37.4	10.0		9.4		8.8	0.290
64	115	0.75	high	1	0	No	18.1	12.5	13.47	Low	1.8	136.8	2.0	94.2	1.6	1.828	1.8	1.291	2.0	0.730
65	410	0.00	low	-1	1	Yes	13.0	12.5	17.02	High	9.4	143.3	10.0	48.0	8.8	3.547	9.4	2.058	10.0	0.327
66	327	0.00	high	1	0	No	30.4	12.5	9.22	High	1.7	428.3	1.0	158.2	1.9	1.298	1.5	1.217	1.0	0.425
67	217	0.75	high	1	1	Yes	18.1	12.5	13.69	Low	3.1	621.0	3.1	232.0	3.0	1.295	3.1	1.034	3.1	0.376
68	406	0.00	low	-1	1	No	13.0	7.1	19.56	High	10.5	138.5	10.9	49.0	10.1	1.934	10.5	2.265	10.9	0.338
69	317	-0.75	med	0	0	No	18.1	12.5	14.66	High	12.6	145.0	12.4	56.2	12.0	2.307	12.2	1.548	12.4	0.358
70	103	0.00	low	-1	0	Yes	13.0	2.1	21.23	Low	8.6	47.2	8.5	27.2	8.5		8.5	1.176	8.5	0.756
71	419	0.00	low	-1	1	No	30.4	2.1	24.31	High	14.7	120.5	14.5	51.7	14.7	1.611	14.6	1.354	14.5	0.458
72	203	0.75	low	-1	1	No	13.0	2.1	22.69	Low	9.3	96.5	9.4	43.6	9.6	2.288	9.5	1.628	9.4	0.495
73	207	-0.75	med	0	1	No	13.0	12.5	18.69	Low	9.9	271.7	10.4	80.2	9.8	2.705	10.1	1.833	10.4	0.341
74	116	0.75	low	-1	0	Yes	18.1	12.5	20.39	Low	10.0	87.8	9.9	43.7	10.2	2.663	10.1	1.325	9.9	0.540
75	224	0.00	low	-1	1	No	30.4	12.5	23.01	Low	13.1	156.0	13.2		12.9	2.761	13.1		13.2	
76	210	0.75	med	0	1	Yes	13.0	12.5	16.44	Low	5.0	459.8	5.0	134.1	5.7	1.782	5.4	1.401	5.0	0.278
77	418	-0.75	high	1	1	Yes	30.4	2.1	16.37	High	7.0	570.2	7.6	169.2	6.6	1.748	7.1	1.768	7.6	0.327
78	309	0.75	high	1	0	Yes	13.0	12.5	11.86	High	4.2	237.8	3.4	97.2	5.0	2.091	4.2	1.146	3.4	0.444
79	126	0.75	high	1	0	No	30.4	12.5	16.00	Low	2.9	235.2	3.6	146.8	3.1	1.396	3.4	1.034	3.6	0.504
80	314	0.75	low	-1	0	No	18.1	2.1	23.55	High	15.1	38.8	15.7	26.7	14.9	5.556	15.3	2.127	15.7	0.621
81	316	-0.75	low	-1	0	Yes	18.1	7.1	20.38	High	12.8	70.3	14.1	23.9	12.6	3.676	13.4	1.603	14.1	0.341
82	122	0.00	low	-1	0	Yes	30.4	7.1	23.84	Low	12.9	49.0	12.6	31.5	12.5	3.315	12.6	2.137	12.6	0.656
83	413	0.75	high	1	1	Yes	18.1	2.1	12.51	High	3.3	636.0	2.9	177.3	3.4	1.083	3.2	1.252	2.9	0.291
84	202	0.00	high	1	1	Yes	13.0	2.1	15.03	Low	0.8	468.8	0.6	52.6	0.5	1.295	0.6	4.515	0.6	0.109
85	108	-0.75	low	-1	0	Yes	13.0	12.5	20.37	Low	10.5	73.3		25.9	9.4	1.757	9.5	1.734		0.418
86	111	-0.75	high	1	0	Yes	18.1	2.1	17.59	Low	3.8	224.3	4.7	100.7	3.5	1.393	4.1	1.379	4.7	0.486
87	311	0.75	med	0	0	Yes	13.0	12.5	13.50	High	4.6	170.7	4.3	75.1	4.5	2.213	4.4	1.265	4.3	0.458
88	127	0.75	low	-1	0	Yes	30.4	12.5	23.34	Low	11.8	76.2	12.2	32.2	11.5	2.467	11.9	1.941	12.2	0.495
89	[illegible]	-0.75	high	1	0	Yes	30.4	12.5	16.18	Low	5.4	377.5	5.8	116.4	4.9	1.688	5.4	1.394	5.8	0.408
90	424	-0.75	low	-1	1	Yes	30.4	12.5	21.34	High	16.6	159.5	16.6	38.8	16.5	2.534	16.6	1.629	16.6	0.237
91	106	0.75	med	0	0	Yes	13.0	7.1	17.57	Low	3.1	140.8	3.2	75.2	3.1	1.187	3.2	1.041	3.2	0.588
92	204	0.75	high	1	1	No	13.0	2.1	17.16	Low	3.4	402.5	3.5	111.0	3.5	0.987	3.5	1.604	3.5	0.290
93	206	0.75	med	0	1	No	13.0	7.1	17.38	Low	4.3	366.7	4.2	87.0	3.4	1.240	3.8	1.828	4.2	0.242
94	423	0.75	low	-1	1	Yes	30.4	7.1	20.90	High	10.5	215.5	10.8	77.0	9.9	1.726	10.4	2.065	10.8	0.370
95	324	0.75	high	1	0	Yes	30.4	7.1	12.28	High	0.2	166.0	0.2	126.0	0.1	1.422	0.2	0.944	0.2	0.612
96	420	0.75	med	0	1	Yes	30.4	2.1	18.48	High	5.1	324.3	5.0	136.0	4.4	1.604	4.7	1.515	5.0	0.467
97	305	-0.75	high	1	0	Yes	13.0	7.1	12.08	High	2.5	244.3	2.6	93.0	2.7	1.835	2.7	1.570	2.6	0.388
98	323	0.75	high	1	0	No	30.4	7.1	11.81	High	0.2	159.2	0.2	103.0	0.0	2.153	0.1	1.243	0.2	0.624
99	404	0.75	high	1	1	No	13.0	2.1	13.55	High	2.9	448.7	4.0	140.0	3.6	1.024	3.8	1.429	4.0	0.319
100	409	0.00	high	1	1	Yes	13.0	12.5	12.01	High	4.6	688.5	4.7	181.0	3.5	1.372	4.1	1.608	4.7	0.280
101	225	0.00	high	1	1	Yes	30.4	12.5	15.42	Low	3.9	693.0	4.1	210.0	3.8	1.688	4.0	1.581	4.1	0.250
102	113	0.75	med	0	0	No	18.1	7.1	15.95	Low	4.1	152.2	4.2	91.0	4.5	1.348	4.4	1.220	4.2	0.569
103	422	0.75	med	0	1	No	30.4	7.1	13.52	High	2.8	403.8	1.7	109.0	3.0	1.509	2.4	2.110	1.7	0.354
104	320	0.75	low	-1	0	Yes	30.4	2.1	24.28	High	15.1	44.8	15.0	30.0	15.0	2.356	15.0		15.0	0.600

Table 32. Resilient modulus and tensile strength test data (continued).

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL ANALYSIS.

Random Cell No.	Group Cell No.	AC X	Compaction Level		AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	Res. Mod. (77 F, 1 Day) AIR VOIDS	Res. Mod. (77 F, 1 Day) MR (ksi)	Ten. Str. (77 F, 1Day) AIR VOIDS	Ten. Str. (77 F, 1Day) TS (psi)	Aged MR Ratio (77 F) AIR VOIDS	Aged MR Ratio (77 F) MR 32day / MR 1day	Aged TS Ratio (77 F) AIR VOIDS	Aged TS Ratio (77 F) TS 32day / TS 1day	TS/MR Ratio (77F,1Day) AIR VOIDS	TS/MR Ratio (77F,1Day) TS/MR
105	109	0.00	high	1	0	No	13.0	12.5	14.48	Low	4.1	198.0	4.0	96.0	4.0	1.800	4.0		4.0	0.530
106	101	-0.75	low	-1	0	No	13.0	2.1	22.11	Low	10.0	32.5	10.5	20.0	9.8	2.031	10.2	2.000	10.5	0.541
107	416	0.75	low	-1	1	No	18.1	12.5	18.87	High	13.0	183.0	13.1	44.0	12.5	2.917	12.8	2.493	13.1	0.216
108	425	-0.75	high	1	1	No	30.4	12.5	10.39	High	6.1	1051.3	4.9	243.0	5.5	1.319	5.2	1.406	4.9	0.280

Table 32. Resilient modulus and tensile strength test data (continued).

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	Slope of Log MR vs Temp: AIR VOIDS	Slope of Log MR vs Temp: SLOPE	Index Retained Modulus: AIR VOIDS	Index Retained Modulus: IRM (77 F)	Index Retained Strength: AIR VOIDS	Index Retained Strength: IRS (77 F)	Aged TS Ratio (0 F): AIR VOIDS	Aged TS Ratio (0 F): TS 32day / TS 1day	Index Retained Strength: AIR VOIDS	Index Retained Strength: IRS (0 F)	Index Retained Modulus: AIR VOIDS	Index Retained Modulus: IRM (Sat, 77F)
1	303	0.75	high	1	0	No	13.0	2.1	12.60	High	2.7	-0.019	4.1	67.7	3.4	81.2	3.9		4.6	56.9	4.8	166.0
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	2.9	-0.030	3.2	113.0	3.1	93.3	3.5	0.700	2.9	107.7	3.0	202.8
3	408	-0.75	med	0	1	Yes	13.0	12.5	15.62	High	9.5	-0.023	8.1	95.7	8.8	169.5	8.3		8.3	155.9	8.2	158.0
4	407	0.75	low	-1	1	Yes	13.0	7.1	18.10	High	9.1	-0.022	8.6	88.1	8.9	77.0	9.8		9.2	104.4	8.9	138.5
5	209	0.00	high	1	1	No	13.0	12.5	16.95	Low	13.1	-0.026	13.7	150.5	13.4	30.1	12.8	0.521	13.4	67.7	13.9	239.9
6	104	0.75	high	1	0	Yes	13.0	2.1	18.19	Low	3.0	-0.023	2.6	167.3	2.8	38.3	2.4	1.245	1.7	116.2	2.1	189.2
7	120	0.75	low	-1	0	No	30.4	2.1	28.47	Low	15.0	-0.021	14.1		14.6		15.0	1.469	14.5	97.0	14.0	218.2
8	220	0.75	high	1	1	No	30.4	2.1	20.45	Low	6.1	-0.027	6.6	164.5	6.4		6.6	0.863	6.4	78.5	6.4	217.5
9	325	-0.75	high	1	0	Yes	30.4	12.5	13.95	High	9.3	-0.020	9.6	124.5	9.5	93.4	9.5	0.977	9.4	126.8	9.4	117.8
10	110	0.75	low	-1	0	No	13.0	12.5	20.44	Low	9.4	-0.018	8.8		9.1		9.3		9.5		9.3	115.7
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	5.2	-0.035	4.8	89.7	5.0	94.2	4.8	0.772	4.1	104.4	4.0	136.8
12	412	0.00	med	0	1	No	18.1	2.1	17.40	High	10.0	-0.034	9.6	51.4	9.8	55.3	8.9	0.866	9.1	81.5	9.5	114.8
13	401	-0.75	high	1	1	Yes	13.0	2.1	24.36	High	17.6	-0.033	15.0	139.9	16.3	143.9	17.6	0.737	18.0	81.9	17.0	132.1
14	114	-0.75	low	-1	0	Yes	18.1	12.5	23.27	Low	14.9	-0.022	14.7	118.8	14.8	145.2	14.7	0.803	14.7	150.4	14.7	129.9
15	124	-0.75	low	-1	0	No	30.4	12.5	12.37	Low	2.7	-0.029	3.7		3.2		3.7		2.8		3.0	129.3
16	307	-0.75	high	1	0	No	13.0	12.5	11.09	High	3.9	-0.022	7.0	38.4	5.4	40.2	3.8	1.542	6.1	36.4	7.7	94.6
17	223	-0.75	med	0	1	Yes	30.4	12.5	19.52	Low	10.1	-0.027	10.8	138.6	10.5	88.1	10.2	1.092	10.3	148.7	10.6	152.3
18	105	0.75	low	-1	0	No	13.0	7.1	20.89	Low	9.0	-0.064	9.3		9.2		9.7		9.5	98.4	9.6	11.4
19	427	0.75	med	0	1	No	30.4	12.0	14.80	High	5.9	-0.033	6.2	64.2	6.1	55.2	5.3	1.089	5.4	90.0	5.9	132.2
20	405	-0.75	low	-1	1	No	13.0	7.1	19.15	High	11.6	-0.034	10.0	81.7	10.8	67.4	11.9		11.8	69.2	10.6	133.7
21	211	0.75	low	-1	1	Yes	13.0	12.5	20.94	Low	9.7	-0.038	10.0	145.9	9.9	100.6	9.8	0.786	10.0	132.6	10.0	145.0
22	402	-0.75	med	0	1	No	13.0	2.1	16.09	High	8.4	-0.036	10.7	58.9	9.6	49.3	9.1		9.1		5.4	
23	417	-0.75	low	-1	1	No	30.4	2.1	24.64	High	15.5	-0.035	16.1	69.6	15.8	65.2	16.5		16.5	122.0	16.3	109.6
24	226	0.75	low	-1	1	No	30.4	12.5	24.06	Low	13.5	-0.033	13.7	86.8	13.6	67.4	13.3		13.0	171.8	13.2	106.8
25	312	0.00	high	1	0	Yes	18.1	2.1	13.10	High	3.5	-0.021	3.3	130.2	3.4	98.6	2.9	1.092	2.7	77.3	3.2	104.2
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	7.8	-0.028	7.5	76.0	7.7	77.0	7.7	0.874	8.0	82.8	8.0	141.3
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	9.3	-0.023	9.2	130.1	9.3	90.9	10.0	1.421	10.6	110.8	10.2	95.3
28	107	-0.75	high	1	0	Yes	13.0	12.5	14.22	Low	5.7	-0.022	5.2	109.2	5.5	92.7	6.0	1.131	6.5	81.6	5.9	123.5
29	302	-0.75	low	-1	0	No	13.0	2.1	19.15	High	11.3	-0.018	11.1	53.3	11.2	69.4	11.1		11.7	54.2	11.4	114.0
30	326	-0.75	low	-1	0	No	30.4	12.5	20.80	High	17.1	-0.029	17.4	38.3	17.3	60.9	16.4	1.040	16.1	56.6	16.8	95.1
31	125	0.00	med	0	0	No	30.4	12.5	16.72	Low	6.6	-0.025	7.1	10.3	6.9	17.9	7.5	0.817	7.7	17.1	7.5	120.1
32	118	-0.75	med	0	0	Yes	30.4	2.1	21.81	Low	9.7	-0.027	9.6	100.0	9.7	106.0	9.5	1.536	9.9	98.1	9.9	108.4
33	414	-0.75	low	-1	1	Yes	18.1	12.5	20.69	High	18.4	-0.021	19.1	122.1	18.8	77.5	18.1	0.604	18.4	361.6	18.8	93.3
34	119	0.75	high	1	0	Yes	30.4	2.1	18.55	Low	2.5	-0.021	2.4	108.1	2.5	96.9	1.9	1.526	1.8	148.6	2.4	107.1
35	310	0.75	low	-1	0	No	13.0	12.5	18.02	High	8.9	-0.021	8.9	51.4	8.9	50.8	8.9		8.6	217.9	8.6	111.6
36	212	-0.75	low	-1	1	No	18.1	2.1	23.96	Low	14.3	-0.035	14.0		14.2		14.6	0.742	14.3		14.0	152.7
37	221	0.75	low	-1	1	Yes	30.4	2.1	25.93	Low	11.2		10.7	100.0	11.0	88.1	11.0	0.736	11.2	135.2	11.0	137.4
38	216	0.75	high	1	1	Yes	18.1	7.1	14.25	Low	2.2	-0.035	1.5	106.3	1.9	89.4	1.1	0.799	1.6	88.7	1.8	131.7
39	117	-0.75	high	1	0	No	30.4	2.1	19.49	Low	6.7	-0.021	6.2	18.6	6.5	21.8	6.9	0.888	6.6	39.0	6.3	115.7
0	208	-0.75	low	-1	1	No	13.0	12.5	19.28	Low	10.9	-0.029	11.8	54.5	11.4	65.7	10.7	0.839	10.0	89.5	10.8	141.1
-1	308	0.00	low	-1	0	No	13.0	12.5	16.59	High	9.4	-0.017	8.6	49.1	9.0	52.8	9.3		9.8	49.8	9.2	118.4
[illegible]	112	0.00	med	0	0	No	18.1	2.1	18.55	Low	6.8	-0.025	6.8	37.5	6.8	56.3	7.7		7.7	97.8	7.4	81.0
43	415	-0.75	high	1	1	No	18.1	12.5	9.76	High	5.3	-0.030	5.1	66.8	5.2	79.2	4.9	1.189	5.4	103.6	5.3	99.3
44	201	-0.75	low	-1	1	Yes	13.0	2.1	22.43	Low	10.8	-0.032	9.8	153.3	10.3	104.8	10.0	0.710	9.7	109.9	9.5	119.8
45	301	-0.75	low	-1	0	Yes	13.0	2.1	18.65	High	11.2	-0.019	11.3	92.5	11.3	85.0	10.3		10.4	138.0	10.7	86.4
46	411	0.75	high	1	1	No	13.0	12.5	10.97	High	1.8	-0.059	1.4	96.4	1.6	90.6	2.1	1.924	1.7	172.1	1.3	105.3
47	102	-0.75	high	1	0	No	13.0	2.1	16.17	Low	4.1	-0.024	4.8	33.8	4.5	33.5	4.5	1.180	4.7	81.1	4.8	108.3
48	319	-0.75	high	1	0	No	30.4	2.1	16.22	High	6.5	-0.025	6.2	47.8	6.4	56.1	6.4	0.924	6.1	81.6	6.1	83.0
49	315	0.75	low	-1	0	Yes	18.1	2.1	23.23	High	9.7	-0.018	9.5	115.9	9.6	99.4	10.2	0.702	9.6	109.9	9.3	104.9
50	215	0.00	low	-1	1	Yes	18.1	7.1	21.93	Low	12.7	0.031	11.9	102.9	12.3	96.2	11.8	1.151	12.0	147.6	12.0	117.9
51	222	-0.75	high	1	1	No	30.4	7.1	16.48	Low	6.3	0.029	6.9	92.4	6.6	9.3	6.3	1.244	6.7	144.7	6.9	144.0
52	421	0.00	high	1	1	Yes	30.4	7.1	12.29	High	2.5	0.030	2.5	101.7	2.5	103.6	3.1		3.6		3.1	202.8

Table 32. Resilient modulus and tensile strength test data (continued).

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL

Random Cell No.	Group Cell No.	AC x	Compaction Level		AC Type	Additive	Percent passing sieve #30	#200	VMA	Aggregate stripping potential	Slope of Log MR vs Temp: AIR VOIDS	SLOPE	Index Retained Modulus: AIR VOIDS	IRM (77 F)	Index Retained Strength: AIR VOIDS	IRS (77 F)	Aged TS Ratio (0 F): AIR VOIDS	TS 32day / TS 1day	Index Retained Strength: AIR VOIDS	IRS (0 F)	Index Retained Modulus: AIR VOIDS	IRM (Sat, 77F)
53	313	0.00	high	1	0	No	18.1	2.1	13.75	High	4.9	-0.026	5.2	56.7	5.1	69.5	5.3	0.967	5.7	99.2	5.7	116.4
54	306	-0.75	med	0	0	No	13.0	7.1	14.30	High	7.0	-0.022	8.1	54.1	7.6	85.8	7.1	0.958	8.1	84.7	8.5	94.2
55	426	0.75	high	1	1	Yes	30.4	12.0	12.78	High	4.9	-0.029	5.0	40.1	5.0	78.2	4.8		5.2	130.0	5.0	96.2
56	213	-0.75	med	0	1	Yes	18.1	2.1	19.32	Low	8.7	-0.032	8.2	216.8	8.5	156.1	9.2		8.7	120.8	8.2	110.4
57	218	-0.75	low	-1	1	Yes	30.4	2.1	28.44	Low	16.9		14.6	116.9	15.8	134.8	14.1	0.761	14.3	161.1	14.6	198.4
58	328	0.75	low	-1	0	Yes	30.4	12.5	20.28	High	11.9	-0.021	12.2	92.3	12.1	103.5	12.1	0.895	12.3	95.4	12.1	79.3
59	121	-0.75	low	-1	0	No	30.4	7.1	23.62	Low	17.0		16.5		16.8	22.4	17.0	1.312	16.9	55.5	16.7	95.5
60	304	0.75	med	0	0	Yes	13.0	2.1	15.39	High	5.9	-0.023	6.6	70.7	6.3	88.2	6.2	1.055	6.7	87.5	6.8	90.3
61	321	0.75	low	-1	0	No	30.4	2.1	24.88	High	12.8		13.9	50.0	13.4	73.7	12.5	0.853	12.5	87.3	13.0	103.0
62	322	0.00	med	0	0	Yes	30.4	7.1	13.40	High	5.3	-0.024	5.9	113.8	5.6	88.5	6.2		5.8		5.9	93.8
63	403	0.75	low	-1	1	Yes	13.0	2.1	18.78	High	8.8		9.1	103.5	9.0	97.1	9.8	0.919	9.2	83.0	8.9	128.0
64	115	0.75	high	1	0	No	18.1	12.5	13.47	Low	2.0	-0.022	4.0	29.3	3.0	64.6	1.8	1.609	3.3	106.1	4.4	88.1
65	410	0.00	low	-1	1	Yes	13.0	12.5	17.02	High	10.0	-0.032	6.5	105.7	8.3	91.5	9.3	1.209	7.4	138.9	5.9	169.6
66	327	0.00	high	1	0	No	30.4	12.5	9.22	High	1.0	-0.025	1.9	57.9	1.5		1.7		1.9		1.9	108.5
67	217	0.75	high	1	1	Yes	18.1	12.5	13.69	Low	3.1	-0.040	3.5	97.1	3.3	92.2	2.9	1.195	3.0	126.3	3.2	127.7
68	406	0.00	low	-1	1	No	13.0	7.1	19.56	High	10.9	-0.040	10.9		10.9		10.6	0.722	10.1	105.6	10.3	185.2
69	317	-0.75	med	0	0	No	18.1	12.5	14.66	High	12.4	-0.025	13.0	40.2	12.7	44.3	12.6	1.096	13.2	186.4	13.0	118.1
70	103	0.00	low	-1	0	Yes	13.0	2.1	21.23	Low	8.5		8.7	78.1	8.6	84.6	8.5		9.0	87.3	9.0	95.6
71	419	0.00	low	-1	1	No	30.4	2.1	24.31	High	14.5		14.8	29.2	14.7	42.9	14.7	0.931	14.9	162.9	14.9	100.3
72	203	0.75	low	-1	1	No	13.0	2.1	22.69	Low	9.4	-0.033	7.8		8.6		10.6	1.075	8.1		7.8	97.7
73	207	-0.75	med	0	1	No	13.0	12.5	18.69	Low	10.4	-0.028	9.9	56.5	10.2	178.3	9.9	1.076	9.7	122.7	9.6	80 0
74	116	0.75	low	-1	0	Yes	18.1	12.5	20.39	Low	9.9	-0.019	10.0	90.1	10.0	91.3	9.7	0.895	9.8	140.2	10.2	86.8
75	224	0.00	low	-1	1	No	30.4	12.5	23.01	Low	13.2	-0.038	13.4	30.7	13.3		13.0	0.962	13.2	140.1	13.4	110.1
76	210	0.75	med	0	1	Yes	13.0	12.5	16.44	Low	5.0	-0.035	5.7	87.4	5.4	99.1	4.7	0.984	4.6	119.4	5.1	142.6
77	418	-0.75	high	1	1	Yes	30.4	2.1	16.37	High	7.6	-0.034	6.9	67.8	7.3	95.7	7.0	0.631	6.9	96.1	6.9	108.8
78	309	0.75	high	1	0	Yes	13.0	12.5	11.86	High	3.4	-0.027	5.5	61.3	4.5	72.2	3.5	1.433	3.8	139.0	4.8	103.4
79	126	0.75	high	1	0	No	30.4	12.5	16.00	Low	3.6	-0.028	3.1	73.6	3.4	56.8	2.7	0.841	2.4	93.1	2.8	92.4
80	314	0.75	low	-1	0	No	18.1	2.1	23.55	High	15.7	-0.002	14.9		15.3	54.7	15.2	0.897	15.2	107.9	15.0	101.7
81	316	-0.75	low	-1	0	Yes	18.1	7.1	20.38	High	14.1	-0.017	12.4	74.7	13.3	90.8	12.1	0.829	12.7	183.3	13.0	77.5
82	122	0.00	low	-1	0	Yes	30.4	7.1	23.84	Low	12.6		12.7	115.2	12.7	98.4	13.3	1.168	13.3	194.4	12.9	102.9
83	413	0.75	high	1	1	Yes	18.1	2.1	12.51	High	2.9	-0.038	3.3	94.7	3.1	92.0	3.3	0.708	3.6	83.9	3.4	94.8
84	202	0.00	high	1	1	Yes	13.0	2.1	15.03	Low	0.6	-0.029	1.3	91.9	1.0	301.3	0.7	0.645	0.9	87.3	1.3	110.8
85	108	-0.75	low	-1	0	Yes	13.0	12.5	20.37	Low			11.9	61.8	11.9	106.9	10.8	0.531	10.5		10.8	92.7
86	111	-0.75	high	1	0	Yes	18.1	2.1	17.59	Low	4.7	-0.027	4.0	63.9	4.4	86.8	3.7	1.028	3.4	110.0	3.7	107.1
87	311	0.75	med	0	0	Yes	13.0	12.5	13.50	High	4.3	-0.023	4.5	63.2	4.4	81.8	4.6	0.830	4.7	65.9	4.9	85.3
88	127	0.75	low	-1	0	Yes	30.4	12.5	23.34	Low	12.2	-0.021	12.4	76.7	12.3	97.8	11.7	1.132	11.9	144.8	12.0	73.7
89	123	-0.75	high	1	0	Yes	30.4	12.5	16.18	Low	5.8	-0.021	5.4	85.6	5.6	94.1	5.2	0.839	5.4	92.0	5.7	78.8
90	424	-0.75	low	-1	1	Yes	30.4	12.5	21.34	High	16.6	-0.030	16.7	67.5	16.7	83.2	16.4	1.029	16.6	298.2	16.8	63.7
91	106	0.75	med	0	0	Yes	13.0	7.1	17.57	Low	3.2	-0.023	3.1	101.5	3.2	77.9	3.4	0.770	3.1	98.7	2.8	103.8
92	204	0.75	high	1	1	No	13.0	2.1	17.16	Low	3.5	-0.036	2.9	81.0	3.2	112.6	3.2	0.516	3.6	93.5	3.4	95.3
93	206	0.75	med	0	1	No	13.0	7.1	17.38	Low	4.2	-0.037	4.4	73.3	4.3	98.9	4.7	0.921	4.6	88.1	4.5	98.7
94	423	0.75	low	-1	1	Yes	30.4	7.1	20.90	High	10.8	-0.038	11.3	71.4	11.1	51.9	10.1	0.810	10.3	138.1	11.0	96.0
95	324	0.75	high	1	0	Yes	30.4	7.1	12.28	High	0.2	-0.031	0.0	81.9	0.1	68.3	0.4	1.191	0.3	94.8	0.1	99.8
96	420	0.75	med	0	1	Yes	30.4	2.1	18.48	High	5.0	-0.033	5.4	61.9	5.2	66.2	5.1	0.667	5.3	85.1	5.6	138.0
97	305	-0.75	high	1	0	Yes	13.0	7.1	12.08	High	2.6	-0.020	3.1	68.1	2.9	79.5	2.0	0.820	2.2	80.0	2.9	127.7
98	323	0.75	high	1	0	No	30.4	7.1	11.81	High	0.2	-0.032	0.2	78.8	0.2	89.3	0.4	0.718	0.2	108.3	0.1	139.8
99	404	0.75	high	1	1	No	13.0	2.1	13.55	High	4.0	-0.035	2.5	71.3	3.3	81.4	2.1	0.758	2.6	67.8	2.9	100.4
100	409	0.00	high	1	1	Yes	13.0	12.5	12.01	High	4.7	-0.033	4.9	68.5	4.8	50.8	4.9	0.902	4.3	118.3	4.7	86.1
101	225	0.00	high	1	1	Yes	30.4	12.5	15.42	Low	4.1	-0.033	4.3	59.6	4.2	90.0	3.7	1.238	3.7		4.0	85.4
102	113	0.75	med	0	0	No	18.1	7.1	15.95	Low	4.2	-0.029	4.2	35.0	4.2	46.2	3.9	0.860	3.6	94.4	4.0	119.6
103	422	0.75	med	0	1	No	30.4	7.1	13.52	High	1.7	-0.036	2.8	74.1	2.3	23.3	3.1	0.667	3.0	85.8	3.0	102.2
104	320	-0.75	low	-1	0	Yes	30.4	2.1	24.28	High	15.0	-0.022	15.0	93.0	15.0	330.7	15.3	1.261	15.1	221.0	15.0	157.3

Table 32. Resilient modulus and tensile strength test data (continued).

DATA BASE DB1. DEPENDENT AND INDEPENDENT VARIABLES FOR STATISTICAL

Random Cell No.	Group Cell No.	AC %	Compaction Level		AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	Slope of Log MR vs Temp: AIR VOIDS	Slope of Log MR vs Temp: SLOPE	Index Retained Modulus: AIR VOIDS	Index Retained Modulus: IRM (77 F)	Index Retained Strength: AIR VOIDS	Index Retained Strength: IRS (77 F)	Aged TS Ratio (0 F): AIR VOIDS	Aged TS Ratio (0 F): TS 32day / TS 1day	Index Retained Strength: AIR VOIDS	Index Retained Strength: IRS (0 F)	Index Retained Modulus: AIR VOIDS	Index Retained Modulus: IRM (Sat,77F)
105	109	0.00	high	1	0	No	13.0	12.5	14.48	Low	4.0	-0.024	4.8		4.4		4.0	1.266	4.0	101.2	4.2	149.7
106	101	-0.75	low	-1	0	No	13.0	2.1	22.11	Low	10.5		10.0		10.3		10.3		9.8		9.7	71.4
107	416	0.75	low	-1	1	No	18.1	12.5	18.87	High	13.1	-0.041	12.7	42.9	12.9	50.0	12.4	0.893	13.7	124.3	14.0	113.9
108	425	-0.75	high	1	1	No	30.4	12.5	10.39	High	4.9	-0.033	7.0	39.8	6.0	34.6	6.6	0.921	6.7	93.3	6.6	122.4

°C = 5(°F-32)/9
1 ksi = 6.89 MPa
1 psi = 6.89 kPa

Test Data

Creep test data are summarized in table 33.

FATIGUE TESTING

A diametral fatigue test procedure was selected to measure fatigue life. A conventional 4-in (102-mm) diameter by 2.5-in (63-mm) high cylindrical specimen was placed in the diametral position between two fixed loading platens. The sample was subjected to a haversine load at 10 Hz. Two samples were tested for each mixture, one at a load of 12 psi (83 kPa) and the second at a load level of 30 psi(207 kPa). Load levels were chosen to fail the median air void mixtures at approximately 5,000 and 100,000 cycles, respectively. These levels were initially established by trial and error after testing several median mixtures and were held constant for the other mixtures.

Failure was defined as the number of load repetitions required to produce 0.5 in (12.7 mm) of deformation in the specimen. Test data is presented in table 34.

DATA REDUCTION

The following formulas were used to reduce the test data presented in tables 32, 33, and 34.

Resilient Modulus and Tensile Strength Data

Resilient Modulus (MR) and Tensile Strength (TS) were calculated as described in ASTM Method D4123.

$$\text{Aged MR Ratio} = \frac{\text{MR 77 °F, 32 days}}{\text{MR 77 °F, 1 day}} \tag{36}$$

$$\text{Aged TS Ratio} = \frac{\text{TS 77 °F, 32 days}}{\text{MR 77 °F, 1 day}} \tag{37}$$

$$\text{TS/MR Ratio} = \frac{\text{TS 77 °F, 1 day}}{\text{MR 77 °F, 1 day}} \tag{38}$$

$$\text{Slope of Log MR vs Temp.} = \frac{\text{Log MR 77 °F - Log MR 104 °F}}{\text{77 °F - 104 °F}} \tag{39}$$

$$\text{Index of Retained Modulus (IRM)} = \frac{\text{MR 77 °F, Wet x 100}}{\text{MR 77 °F, 1 day}} \tag{40}$$

Table 33. Laboratory creep data.

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	CREEP TEST DATA: MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	TOTAL VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRSSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	0	7.326	60	0.01146	0.0015643	0.0001304	7671	
											7.326	600	0.01694	0.0023123	0.0001927	5190	
											7.326	1200	0.01913	0.0026112	0.0002176	4596	
											7.326	2400	0.02217	0.0030262	0.0002522	3965	
											7.326	3600	0.02457	0.0033538	0.0002795	3578	
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	1	7.295	60	0.00917	0.0012570	0.0001048	9546	1.244
											7.295	600	0.01211	0.0016600	0.0001383	7229	1.393
											7.295	1200	0.01365	0.0018711	0.0001559	6413	1.396
											7.295	2400	0.01594	0.0021851	0.0001821	5492	1.385
											7.295	3600	0.01709	0.0023427	0.0001952	5122	1.432
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	0	7.278	60	0.01495	0.0020541	0.0001712	5842	
											7.278	600	0.02471	0.0033952	0.0002829	3534	
											7.278	1200	0.03020	0.0041495	0.0003458	2892	
											7.278	2400	0.04390	0.0060319	0.0005027	1989	
											7.278	3600	0.07649	0.0105098	0.0008758	1142	
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	1	7.586	60	0.01066	0.0014052	0.0001171	8540	1.462
											7.586	600	0.01709	0.0022528	0.0001877	5327	1.507
											7.586	1200	0.02038	0.0026865	0.0002239	4467	1.545
											7.586	2400	0.02586	0.0034089	0.0002841	3520	1.769
											7.586	3600	0.03281	0.0043251	0.0003604	2775	2.430
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	0	7.327	60	0.01031	0.0014071	0.0001173	8528	
											7.327	600	0.01969	0.0026873	0.0002239	4465	
											7.327	1200	0.03046	0.0041572	0.0003464	2887	
											7.327	2400	0.04639	0.0063314	0.0005276	1895	
											7.327	3600	0.05087	0.0069428	0.0005786	1728	
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	1	7.581	60	0.00668	0.0008812	0.0000734	13619	1.597
											7.581	600	0.00842	0.0011107	0.0000926	10804	2.420
											7.581	1200	0.00902	0.0011898	0.0000992	10086	3.494
											7.581	2400	0.01081	0.0014259	0.0001188	8416	4.440
											7.581	3600	0.0137	0.0018071	0.0001506	6640	3.842
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	0	7.429	60	0.00588	0.0007915	0.0000660	15161	
											7.429	600	0.00618	0.0008319	0.0000693	14425	
											7.429	1200	0.00623	0.0008386	0.0000699	14309	
											7.429	2400	0.00638	0.0008588	0.0000716	13973	
											7.429	3600	0.00105	0.0001413	0.0000118	84903	
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	1	7.369	60	0.00737	0.0010001	0.0000833	11998	0.791
											7.369	600	0.00917	0.0012444	0.0001037	9643	0.668
											7.369	1200	0.00987	0.0013394	0.0001116	8959	0.626

Table 33. Laboratory creep data (continued).

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	TOTAL VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRSSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
											7.369	2400	0.01131	0.0015348	0.0001279	7819	0.560
											7.369	3600	0.01211	0.0016434	0.0001369	7302	0.086
62	322	0.00	med	0	0 Yes	30.4	7.1	13.40	High	0	7.497	60	0.00997	0.0013299	0.0001108	9023	
											7.497	600	0.01405	0.0018741	0.0001562	6403	
											7.497	1200	0.01599	0.0021329	0.0001777	5626	
											7.497	2400	0.01829	0.0024396	0.0002033	4919	
											7.497	3600	0.00419	0.0005589	0.0000466	21471	
62	322	0.00	med	0	0 Yes	30.4	7.1	13.40	High	1	7.529	60	0.01266	0.0016815	0.0001401	7136	0.791
											7.529	600	0.02091	0.0027773	0.0002314	4321	0.675
											7.529	1200	0.02411	0.0032023	0.0002669	3747	0.666
											7.529	2400	0.02762	0.0036685	0.0003057	3271	0.665
											7.529	3600	0.02989	0.0039700	0.0003308	3023	0.141
99	404	0.75	high	1	1 No	13.0	2.1	13.55	High	0	7.205	60	0.00792	0.0010992	0.0000916	10917	
											7.205	600	0.01026	0.0014240	0.0001187	8427	
											7.205	1200	0.01156	0.0016044	0.0001337	7479	
											7.205	2400	0.01301	0.0018057	0.0001505	6646	
											7.205	3600	0.01435	0.0019917	0.0001660	6025	
99	404	0.75	high	1	1 No	13.0	2.1	13.55	High	1	7.279	60	0.00879	0.0012076	0.0001006	9937	0.910
											7.279	600	0.01241	0.0017049	0.0001421	7039	0.835
											7.279	1200	0.01395	0.0019165	0.0001597	6262	0.837
											7.279	2400	0.01583	0.0021747	0.0001812	5518	0.830
											7.279	3600	0.0175	0.0024042	0.0002003	4991	0.828
103	422	0.75	med	0	1 No	30.4	7.1	13.52	High	0	7.369		NO DATA				
													NO DATA				
													NO DATA				
													NO DATA				
													NO DATA				
103	422	0.75	med	0	1 No	30.4	7.1	13.52	High	1	7.229	60	0.01266	0.0017513	0.0001459	6852	
											7.229	600	0.02091	0.0028925	0.0002410	4149	
											7.229	1200	0.02411	0.0033352	0.0002779	3598	
											7.229	2400	0.02762	0.0038207	0.0003184	3141	
											7.229	3600	0.02989	0.0041347	0.0003446	2902	
105	109	0.00	high	1	0 No	13.0	12.5	14.48	Low	0	6.74	60	0.0146	0.0021662	0.0001805	5540	
											6.74	600	0.02158	0.0032018	0.0002668	3748	
											6.74	1200	0.02927	0.0043427	0.0003619	2763	
											6.74	2400	0.03948	0.0058576	0.0004881	2049	
											6.74	3600	0.04423	0.0065623	0.0005469	1829	

Table 33. Laboratory creep data (continued).

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	CREEP TEST DATA: MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	TOTAL VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRSSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
105	109	0.00	high	1	0	No 13.0	12.5	14.48	Low	1	6.576	60	0.02038	0.0030991	0.0002583	3872	0.699
											6.576	600	0.03234	0.0049179	0.0004098	2440	0.651
											6.576	1200	0.03523	0.0053574	0.0004464	2240	0.811
											6.576	2400	0.03682	0.0055991	0.0004666	2143	1.046
											6.576	3600	0.03682	0.0055991	0.0004666	2143	1.172

Table 33. Laboratory creep data (continued).

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	CENTER VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRESSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	0	2.884	60	0.00075	0.0002601	0.0000217	46144	
											2.884	600	0.00092	0.0003190	0.0000266	37617	
											2.884	1200	0.00115	0.0003988	0.0000332	30094	
											2.884	2400	0.00122	0.0004230	0.0000353	28367	
											2.884	3600	0.00135	0.0004681	0.0000390	25636	
2	205	-0.75	high	1	1	Yes	13.0	7.1	14.54	Low	1	2.879	60	0.00086	0.0002987	0.0000249	40172	0.871
											2.879	600	0.00126	0.0004377	0.0000365	27419	0.729
											2.879	1200	0.00149	0.0005175	0.0000431	23187	0.770
											2.879	2400	0.00167	0.0005801	0.0000483	20687	0.729
											2.879	3600	0.00177	0.0006148	0.0000512	19519	0.761
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	0	2.851	60	0.00184	0.0006454	0.0000538	18593	
											2.851	600	0.00513	0.0017994	0.0001499	6669	
											2.851	1200	0.00683	0.0023957	0.0001996	5009	
											2.851	2400	0.01288	0.0045177	0.0003765	2656	
											2.851	3600	0.12327	0.0432375	0.0036031	278	
11	219	0.00	high	1	1	No	30.4	2.1	19.34	Low	1	2.851	60	0.00060	0.0002105	0.0000175	57020	3.067
											2.851	600	0.00105	0.0003683	0.0000307	32583	4.886
											2.851	1200	0.00125	0.0004384	0.0000365	27370	5.464
											2.851	2400	0.00344	0.0012066	0.0001005	9945	3.744
											2.851	3600	0.00523	0.0018344	0.0001529	6541	23.570
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	0	2.862	60	0.00264	0.0009224	0.0000769	13009	
											2.862	600	0.00429	0.0014990	0.0001249	8006	
											2.862	1200	0.00553	0.0019322	0.0001610	6210	
											2.862	2400	0.00777	0.0027149	0.0002262	4420	
											2.862	3600	0.00932	0.0032565	0.0002714	3685	
26	214	-0.75	high	1	1	No	18.1	7.1	14.82	Low	1	2.853	60	0.00110	0.0003856	0.0000321	31124	2.392
											2.853	600	0.00140	0.0004907	0.0000409	24454	3.055
											2.853	1200	0.00159	0.0005573	0.0000464	21532	3.467
											2.853	2400	0.00214	0.0007501	0.0000625	15998	3.619
											2.853	3600	0.00274	0.0009604	0.0000800	12495	3.391
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	0	2.823	60	0.00090	0.0003188	0.0000266	37640	
											2.823	600	0.00095	0.0003365	0.0000280	35659	
											2.823	1200	0.00115	0.0004074	0.0000339	29457	
											2.823	2400	0.00100	0.0003542	0.0000295	33876	
											2.823	3600	0.00105	0.0003719	0.0000310	32263	
27	318	0.00	med	0	0	Yes	18.1	12.5	14.38	High	1	2.873	60	0.00130	0.0004525	0.0000377	26520	0.705
											2.873	600	0.00130	0.0004525	0.0000377	26520	0.744
											2.873	1200	0.00120	0.0004177	0.0000348	28730	0.975

Table 33. Laboratory creep data (continued).

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	CENTER VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRESSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
											2.873	2400	0.00140	0.0004873	0.0000406	24626	0.727
											2.873	3600	0.00125	0.0004351	0.0000363	27581	0.855
62	322	0.00	med	0	0 Yes	30.4	7.1	13.40	High	0	2.832	60	0.00100	0.0003531	0.0000294	33984	
											2.832	600	0.00199	0.0007027	0.0000586	17077	
											2.832	1200	0.00269	0.0009499	0.0000792	12633	
											2.832	2400	0.00344	0.0012147	0.0001012	9879	
											2.832	3600	0.00419	0.0014795	0.0001233	8111	
62	322	0.00	med	0	0 Yes	30.4	7.1	13.40	High	1	2.861	60	0.00149	0.0005208	0.0000434	23042	0.678
											2.861	600	0.00274	0.0009577	0.0000798	12530	0.734
											2.861	1200	0.00304	0.0010626	0.0000885	11293	0.894
											2.861	2400	0.00356	0.0012443	0.0001037	9644	0.976
											2.861	3600	0.00414	0.0014470	0.0001206	8293	1.022
99	404	0.75	high	1	1 No	13.0	2.1	13.55	High	0	2.853	60	0.00040	0.0001402	0.0000117	85590	
											2.853	600	0.00045	0.0001577	0.0000131	76080	
											2.853	1200	0.00050	0.0001753	0.0000146	68472	
											2.853	2400	0.00045	0.0001577	0.0000131	76080	
											2.853	3600	0.00045	0.0001577	0.0000131	76080	
99	404	0.75	high	1	1 No	13.0	2.1	13.55	High	1	2.868	60	0.00184	0.0006416	0.0000535	18704	0.219
											2.868	600	0.00214	0.0007462	0.0000622	16082	0.211
											2.868	1200	0.00234	0.0008159	0.0000680	14708	0.215
											2.868	2400	0.00386	0.0013459	0.0001122	8916	0.117
											2.868	3600	0.00381	0.0013285	0.0001107	9033	0.119
103	422	0.75	med	0	1 No	30.4	7.1	13.52	High	0		60	NO DATA				
												600	NO DATA				
												1200	NO DATA				
												2400	NO DATA				
												3600	NO DATA				
103	422	0.75	med	0	1 No	30.4	7.1	13.52	High	1	2.813	60	0.00149	0.0005297	0.0000441	22655	
											2.813	600	0.00274	0.0009740	0.0000812	12320	
											2.813	1200	0.00304	0.0010807	0.0000901	11104	
											2.813	2400	0.00356	0.0012656	0.0001055	9482	
											2.813	3600	0.00414	0.0014717	0.0001226	8154	
105	109	0.00	high	1	0 No	13.0	12.5	14.48	Low	0	2.856	60	0.00249	0.0008718	0.0000727	13764	
											2.856	600	0.00249	0.0008718	0.0000727	13764	
											2.856	1200	0.00249	0.0008718	0.0000727	13764	
											2.856	2400	0.00248	0.0008683	0.0000724	13819	
											2.856	3600	0.00249	0.0008718	0.0000727	13764	

Table 33. Laboratory creep data (continued).

Random Cell No.	Group Cell No.	AC %	Compaction Level	AC Type	Additive	Percent passing sieve #30	Percent passing sieve #200	VMA	Aggregate stripping potential	MOISTURE CONDITIONED Y=1 N=0	ORIGINAL HEIGHT OF SAMPLE	LOADING TIME SEC	CENTER VERTICAL DEFORMATION IN.	COMPRESSIVE CREEP STRAIN IN/IN	COMPRESSIVE CREEP COMPLIANCE 1/PSI	COMPRESSIVE CREEP MODULUS PSI	RATIO MOIST MOD TO DRY MOD
105	109	0.00	high	1	0	No	13.0	12.5	14.48	Low	1	2.846	60	0.00902	0.0031694	0.0002641	3786	0.275
												2.846	600	0.01066	0.0037456	0.0003121	3204	0.233
												2.846	1200	0.01116	0.0039213	0.0003268	3060	0.222
												2.846	2400	0.01176	0.0041321	0.0003443	2904	0.210
												2.846	3600	0.01211	0.0042551	0.0003546	2820	0.205

1 in = 25.4 mm
1 psi = 6.89 kPa

Table 34. Diametral fatigue testing data.

°C = 5(°F-32)/9
1 psi = 6.89 kPa

DATA BASE DBF1. DIAMETRAL FATIGUE TESTING DATA.

Random Cell No.	Group Cell No.	AC %	Compaction	AC Type	Additive	Percent Passing Sieve #30	Percent Passing Sieve #200	VMA	Aggregate Stripping Potential	Res. Mod. (77F, 1 Day) AIR VOIDS	Res. Mod. (77F, 1 Day) MR	Ten. Str. (77F, 1Day) AIR VOIDS	Ten. Str. (77F, 1Day) TS	Index Retained Modulus AIR VOIDS	Index Retained Modulus IRM (77 F)	Index Retained Strength AIR VOIDS	Index Retained Strength IRS (77 F)	Fatigue Data Cycles to failure	Fatigue Data Stress Level (psi)	Fatigue Data Treatment 0=No;1=Yes
2	205	-0.75	hi	1	1	0	13.0	7.1	14.54	30.0	3.0	401.2	2.9	171.1	3.2	113.0	3.1	93.3	13645	12	0
11	219	0.00	hi	1	1	1	30.4	2.1	19.34	30.0	4.5	306.5	5.2	155.1	4.8	89.7	5.0	94.2	72917	12	0
21	211	0.75	low	-1	1	0	13.0	12.5	20.94	30.0	9.8	137.2	9.7	64.0	10.0	145.9	9.9	100.6	11197	12	0
26	214	-0.75	hi	1	1	1	18.1	7.1	14.82	30.0	7.7	588.8	7.8	228.7	7.5	76.0	7.7	77.0	202055	12	0
27	318	0.00	med	0	0	0	18.1	12.5	14.38	80.0	10.0	219.7	9.3	84.5	9.2	130.1	9.3	90.9	128846	12	0
50	215	0.00	low	-1	1	0	18.1	7.1	21.93	30.0	12.1	175.5	12.7	61.3	11.9	102.9	12.3	96.2	8853	12	0
62	322	0.00	med	0	0	0	30.4	7.1	13.40	80.0	5.9	284.3	5.3	115.1	5.9	113.8	5.6	88.5	133603	12	0
74	116	0.75	low	-1	0	0	18.1	12.5	20.39	30.0	10.0	87.8	9.9	43.7	10.0	90.1	10.0	91.3	3882	12	0
90	424	-0.75	low	-1	1	0	30.4	12.5	21.34	80.0	16.6	159.5	16.6	38.8	16.7	67.5	16.7	83.2	2683	12	0
99	404	0.75	hi	1	1	1	13.0	2.1	13.55	80.0	2.9	448.7	4.0	140.0	2.5	71.3	3.3	81.4	152628	12	0
103	422	0.75	med	0	1	1	30.4	7.1	13.52	80.0	2.8	403.8	1.7	109.0	2.8	74.1	2.3	23.3	62278	12	0
105	109	0.00	hi	1	0	1	13.0	12.5	14.48	30.0	4.1	198.0	4.0	96.0	4.8		4.4		5800	12	0
2	205	-0.75	hi	1	1	0	13.0	7.1	14.54	30.0	3.0	401.2	2.9	171.1	3.2	113.0	3.1	93.3	19545	30	0
11	219	0.00	hi	1	1	1	30.4	2.1	19.34	30.0	4.5	306.5	5.2	155.1	4.8	89.7	5.0	94.2	7484	30	0
21	211	0.75	low	-1	1	0	13.0	12.5	20.94	30.0	9.8	137.2	9.7	64.0	10.0	145.9	9.9	100.6	1292	30	0
26	214	-0.75	hi	1	1	1	18.1	7.1	14.82	30.0	7.7	588.8	7.8	228.7	7.5	76.0	7.7	77.0	16860	30	0
27	318	0.00	med	0	0	0	18.1	12.5	14.38	80.0	10.0	219.7	9.3	84.5	9.2	130.1	9.3	90.9	18647	30	0
50	215	0.00	low	-1	1	0	18.1	7.1	21.93	30.0	12.1	175.5	12.7	61.3	11.9	102.9	12.3	96.2	846	30	0
62	322	0.00	med	0	0	0	30.4	7.1	13.40	80.0	5.9	284.3	5.3	115.1	5.9	113.8	5.6	88.5	4053	30	0
74	116	0.75	low	-1	0	0	18.1	12.5	20.39	30.0	10.0	87.8	9.9	43.7	10.0	90.1	10.0	91.3	291	30	0
90	424	-0.75	low	-1	1	0	30.4	12.5	21.34	80.0	16.6	159.5	16.6	38.8	16.7	67.5	16.7	83.2	281	30	0
99	404	0.75	hi	1	1	1	13.0	2.1	13.55	80.0	2.9	448.7	4.0	140.0	2.5	71.3	3.3	81.4	8605	30	0
103	422	0.75	med	0	1	1	30.4	7.1	13.52	80.0	2.8	403.8	1.7	109.0	2.8	74.1	2.3	23.3	5413	30	0
105	109	0.00	hi	1	0	1	13.0	12.5	14.48	30.0	4.1	198.0	4.0	96.0	4.8		4.4		11800	30	0
2	205	-0.75	hi	1	1	0	13.0	7.1	14.54	30.0	3.0	401.2	2.9	171.1	3.2	113.0	3.1	93.3	353333	12	1
11	219	0.00	hi	1	1	1	30.4	2.1	19.34	30.0	4.5	306.5	5.2	155.1	4.8	89.7	5.0	94.2	72865	12	1
21	211	0.75	low	-1	1	0	13.0	12.5	20.94	30.0	9.8	137.2	9.7	64.0	10.0	145.9	9.9	100.6	16598	12	1
26	214	-0.75	hi	1	1	1	18.1	7.1	14.82	30.0	7.7	588.8	7.8	228.7	7.5	76.0	7.7	77.0	200000	12	1
27	318	0.00	med	0	0	0	18.1	12.5	14.38	80.0	10.0	219.7	9.3	84.5	9.2	130.1	9.3	90.9	204726	12	1
50	215	0.00	low	-1	1	0	18.1	7.1	21.93	30.0	12.1	175.5	12.7	61.3	11.9	102.9	12.3	96.2	5401	12	1
62	322	0.00	med	0	0	0	30.4	7.1	13.40	80.0	5.9	284.3	5.3	115.1	5.9	113.8	5.6	88.5	176001	12	1
74	116	0.75	low	-1	0	0	18.1	12.5	20.39	30.0	10.0	87.8	9.9	43.7	10.0	90.1	10.0	91.3	3657	12	1
90	424	-0.75	low	-1	1	0	30.4	12.5	21.34	80.0	16.6	159.5	16.6	38.8	16.7	67.5	16.7	83.2	4856	12	1
99	404	0.75	hi	1	1	1	13.0	2.1	13.55	80.0	2.9	448.7	4.0	140.0	2.5	71.3	3.3	81.4	7914	12	1
103	422	0.75	med	0	1	1	30.4	7.1	13.52	80.0	2.8	403.8	1.7	109.0	2.8	74.1	2.3	23.3	23153	12	1
105	109	0.00	hi	1	0	1	13.0	12.5	14.48	30.0	4.1	198.0	4.0	96.0	4.8		4.4		20447	12	1
2	205	-0.75	hi	1	1	0	13.0	7.1	14.54	30.0	3.0	401.2	2.9	171.1	3.2	113.0	3.1	93.3	23800	30	1
11	219	0.00	hi	1	1	1	30.4	2.1	19.34	30.0	4.5	306.5	5.2	155.1	4.8	89.7	5.0	94.2	3022	30	1
21	211	0.75	low	-1	1	0	13.0	12.5	20.94	30.0	9.8	137.2	9.7	64.0	10.0	145.9	9.9	100.6	671	30	1
26	214	-0.75	hi	1	1	1	18.1	7.1	14.82	30.0	7.7	588.8	7.8	228.7	7.5	76.0	7.7	77.0	5184	30	1
27	318	0.00	med	0	0	0	18.1	12.5	14.38	80.0	10.0	219.7	9.3	84.5	9.2	130.1	9.3	90.9	19979	30	1
50	215	0.00	low	-1	1	0	18.1	7.1	21.93	30.0	12.1	175.5	12.7	61.3	11.9	102.9	12.3	96.2	906	30	1
62	322	0.00	med	0	0	0	30.4	7.1	13.40	80.0	5.9	284.3	5.3	115.1	5.9	113.8	5.6	88.5	6853	30	1
74	116	0.75	low	-1	0	0	18.1	12.5	20.39	30.0	10.0	87.8	9.9	43.7	10.0	90.1	10.0	91.3	313	30	1
90	424	-0.75	low	-1	1	0	30.4	12.5	21.34	80.0	16.6	159.5	16.6	38.8	16.7	67.5	16.7	83.2	222	30	1
99	404	0.75	hi	1	1	1	13.0	2.1	13.55	80.0	2.9	448.7	4.0	140.0	2.5	71.3	3.3	81.4	5001	30	1
103	422	0.75	med	0	1	1	30.4	7.1	13.52	80.0	2.8	403.8	1.7	109.0	2.8	74.1	2.3	23.3	1300	30	1
105	109	0.00	hi	1	0	1	13.0	12.5	14.48	30.0	4.1	198.0	4.0	96.0	4.8		4.4		91	30	1

$$\text{Index of Retained Tensile Strength (IRS)} = \frac{\text{TS 77 °F, Wet x 100}}{\text{TS 77 °F, 1 day}} \quad (41)$$

$$\text{Aged TS Ratio, 0 °F} = \frac{\text{TS 0 °F, 32 days}}{\text{TS 0 °F, 1 day}} \quad (42)$$

$$\text{Index of Retained Strength, 0 °F} = \frac{\text{TS 0 °F, Wet}}{\text{TS 0 °F, 1 day}} \quad (43)$$

$$\text{Index of Retained Modulus, 0 °F} = \frac{\text{MR 0 °F, Wet}}{\text{MR 0 °F, 1 day}} \quad (44)$$

Creep Test Data

$$\text{Creep Compliance, } [D(t) = \epsilon(t)/\sigma] \quad (45)$$

where

$\epsilon(t)$ = $D(t)/G$ = uniaxial unit strain

$\Delta(t)$ = uniaxial deformation with time

G = gage length

σ = applied stress, psi

$$\text{Creep Modulus} = 1/\text{compliance} = \frac{1}{\Delta(t)} \quad (46)$$

Fatigue Test Data

Failure is defined as the number of recommendations required to produce a deformation of 0.5 in (12.7 mm) in the specimen.

APPENDIX D
ANALYSIS METHODS

INTRODUCTION

A major objective for the laboratory study was to establish relationships between materials and construction (M&C) variables and fundamental response variables.

Basic data for development of the relationships are given in tables 32, 33, and 34 in appendix C. Table 32 represents the summary data for the main testing, table 33 shows the data for the permanent deformation tests, and table 34 is a summary of fatigue results.

REGRESSION VARIABLES

Individual regression variables for the main experiment are listed below.

Independent Variables. The percent deviation from optimum asphalt content (%ASPHDEV), the compaction level (COMP), the asphalt type (ASPHTYP), the percent passing sieve #30 (%#30), the percent passing sieve #200 (%#200), the nonstripping additive (ADITV), and the aggregate type (AGGTYP) were the basic independent variables used in this study. The regression analyses include the two-factor interactions of these variables as well as some power functions, e.g., squares or fourth powers, of the basic variables.

Dependent Variables. The dependent variables for the main experiment were as follows.

- Resilient Modulus (MR), 77 °F (25 °C) and 1 day.
- Tensile Strength (TS), 77 °F (25 °C) and 1 day.
- Aged MR ratio (AGMRR), defined as the ratio of resilient modulus at 77 °F (25 °C) and 32 days to the resilient modulus at 77 °F (25 °C) and 1 day.
- Aged TS ratio (AGTSR), defined as the ratio of the tensile strength at 77 °F (25 °C) and 32 days to the tensile strength at 77 °F (25 °C) and 1 day.
- Tensile strength to resilient modulus ratio (TSMR).
- Slope of log MR versus temperature (MTEMP). This was defined as the difference between the common logarithm of MR at 77 °F (25 °C) and the common logarithm of MR at 104 °F (40 °C) over the difference in temperatures.
- Index of retained modulus (IRM).
- Index of retained strength (IRS).

- Aged TS ratio at 0 °F (-18 °C) (AGTSROF).

- TS ratio of wet samples at 0 °F (-18 °C) (TSWETROF).

- MR ratio of saturated samples at 77 °F (25 °C) (MRSATR).

Independent and/or dependent variables. The voids in mineral aggregate (VMA) and the percent air voids (%AIR) were used either as dependent or independent variables.

STATISTICAL ANALYSIS

The data in table 32 were analyzed using SPSS/PC+ software to obtain mean values, box plots, spread level plots and linear regression equations.

Data Examination. Table 35 represents the mean values of MR by aggregate stripping potential (aggregate type) and asphalt type. The asphalt type A is the Boscan (Amoco AC-20) low temperature susceptibility asphalt; the asphalt type B is the Witco (Witco AR-4000) high temperature susceptibility asphalt (see table 22 for asphalt cement properties). A corresponding plot of the mean values in table 35 is shown in figure 46. Table 36 represents MR mean values by compaction level and percent asphalt content. These values have been plotted in figure 47. Similar tables and figures were developed for the tensile strength. The results are presented in tables 37 and 38, and figures 48 and 49, respectively.

Figure 48 for the tensile strength shows the strength of the high temperature susceptibility asphalt selected for this experiment to be more sensitive to changes in aggregate type.

Figures 47 and 49 for the resilient modulus and the tensile strength, respectively, show a significant effect of compaction on the strength of the tested samples. At medium (optimum) asphalt content the reduction in resilient modulus from the high compaction level to the low compaction level is of the order of 76 percent. In the case of the tensile strength a similar reduction (74 percent) in strength is observed. In addition, both figures show the nonlinear effect of the percent asphalt content.

Mean values for the effect of the sieve No. 200 (75 μm) are shown in tables 39 and 40 for the resilient modulus and the tensile strength, respectively. Figures 50 and 51 are the corresponding plots of the values in these tables. In general, the trend shown in the plots indicate a nonlinear effect of the sieve No. 200 (75 μm) on the strength of the tested samples. The effect of the sieve No. 200 (75 μm) is more significant for the design mix (high compaction and medium percent asphalt content).

Most of the trends shown in the figures above agree with engineering judgement, but interpretation of results should be done carefully since standard deviations for some mean values are as high as 92 percent. Figures 52 and 53 are box plots for resilient modulus and tensile strength respectively corresponding to values in tables 35 and 37. It can be observed that, in both cases (resilient modulus and tensile strength), the variability for asphalt type B is greater than for asphalt A.

Table 35. Resilient modulus (ksi) mean values by aggregate and asphalt type.

			Aggregate Type		
			Stripping Potential		Row Totals
			High	Low	
Asphalt Type	A Boscan	x =	127.6	154.8	141.4
		s =	91.9	105.7	99.2
		n =	27	28	55
	B Witco		324.6	399.5	362.8
			215.7	297.2	260.7
			26	27	53
Column Totals			224.2	274.9	250.1
			191.0	251.7	224.4
			53	55	108

x = Mean value 1 ksi = 6.89 MPa
s = Standard deviation
n = Number of cases

Table 36. Resilient modulus (ksi) mean values by compaction levels and percent asphalt content.

			Compaction Level			Row Totals
			Low	Medium	High	
Percent Asphalt	-0.75	x =	75.1	200.3	448.4	241.2
		s =	38.7	67.1	298.0	251.2
		n =	18	8	16	42
	0		109.6	237.8	463.0	291.1
			53.6	107.9	209.4	216.9
			8	5	10	23
	0.75		101.8	299.1	353.7	236.8
			74.4	153.4	238.5	202.2
			18	9	16	43
Column Totals			92.3	249.2	415.8	250.1
			58.9	121.2	255.7	224.4
			44	22	42	108

x = Mean value 1 ksi = 6.89 MPa
s = Standard deviation
n = Number of cases

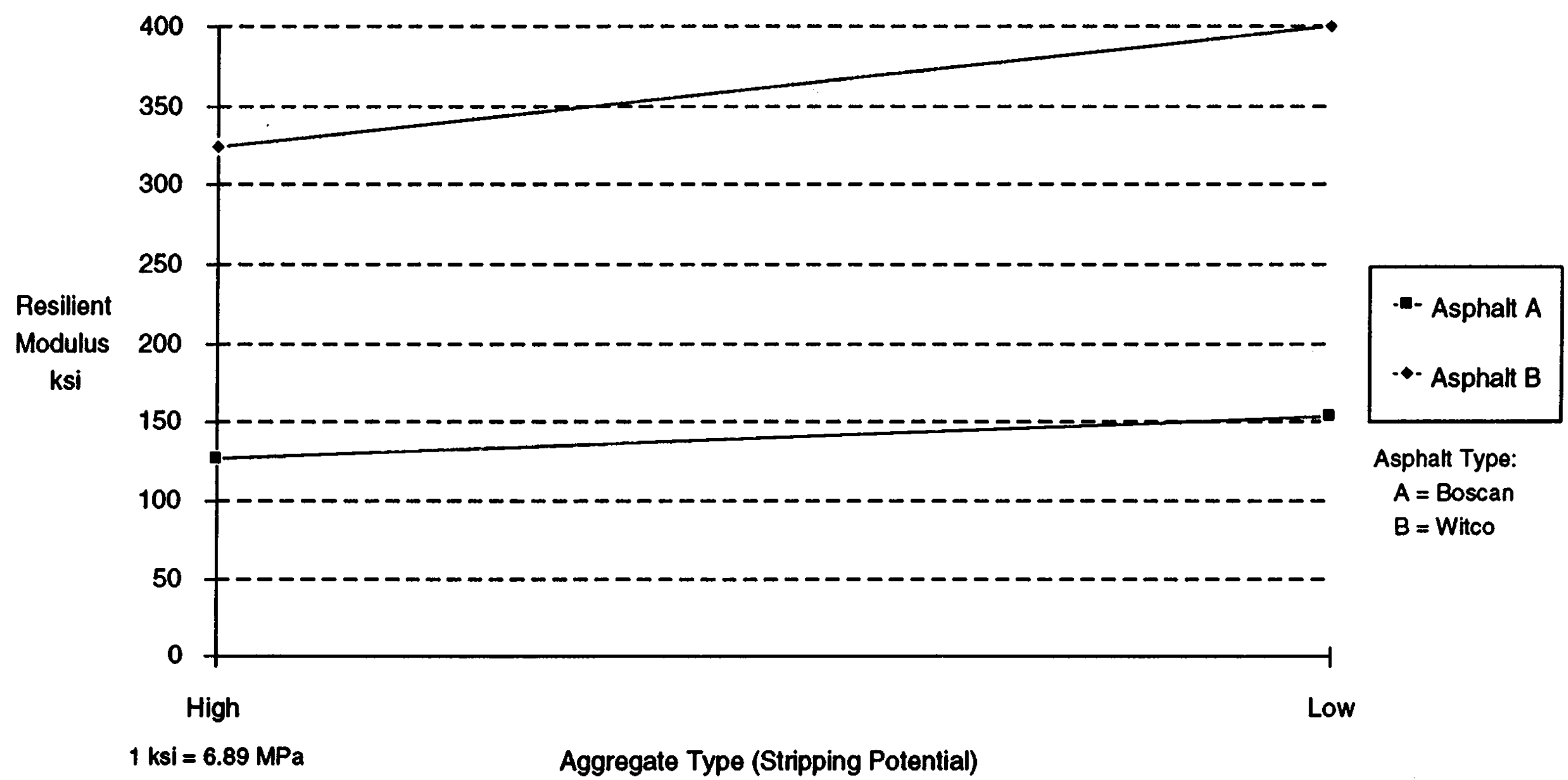


Figure 46. Effect of asphalt & aggregate type on resilient modulus (77 °F [25 °C]).

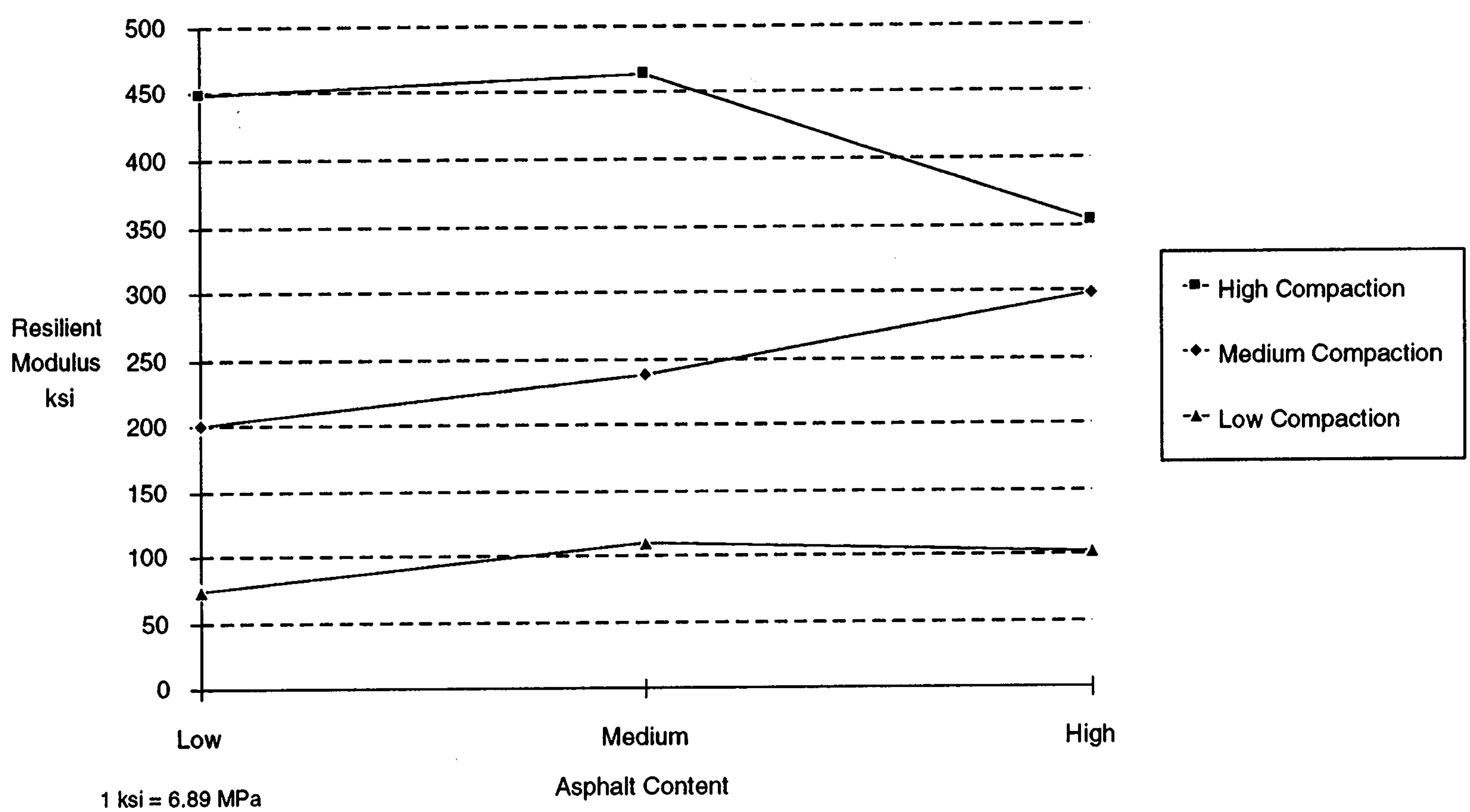


Figure 47. Effect of compaction & asphalt content on resilient modulus (77 °F [25 °C]).

Table 37. Tensile strength (psi) mean values by aggregate and asphalt type.

			Aggregate Type: Stripping Potential High	Aggregate Type: Stripping Potential Low	Row Totals
Asphalt Type	A Boscan	x =	68.8	69.5	69.2
		s =	40.5	41.9	40.8
		n =	27	28	55
	B Witco		128.5	115.9	121.9
			83.8	72.0	77.4
			25	27	52
Column Totals			97.5	92.3	94.8
			71.0	62.6	66.6
			52	55	107

x = Mean value 1 psi = 6.89 kPa
s = Standard deviation
n = Number of cases

Table 38. Tensile strength (psi) mean values by compaction level and percent asphalt content.

			Compaction Level: Low	Compaction Level: Medium	Compaction Level: High	Row Totals
Percent Asphalt	-0.75	x =	31.5	78.4	154.4	87.2
		s =	11.6	26.7	64.5	69.6
		n =	18	8	16	42
	0		42.0	97.3	158.6	107.6
			13.9	22.9	65.8	68.6
			7	5	10	22
	0.75		42.3	103.8	151.3	95.7
			14.5	37.9	57.8	62.9
			18	9	16	43
Column Totals			37.7	93.1	154.2	94.8
			14.0	31.9	60.8	66.6
			43	22	42	107

x = Mean value 1 psi = 6.89 kPa
s = Standard deviation
n = Number of cases

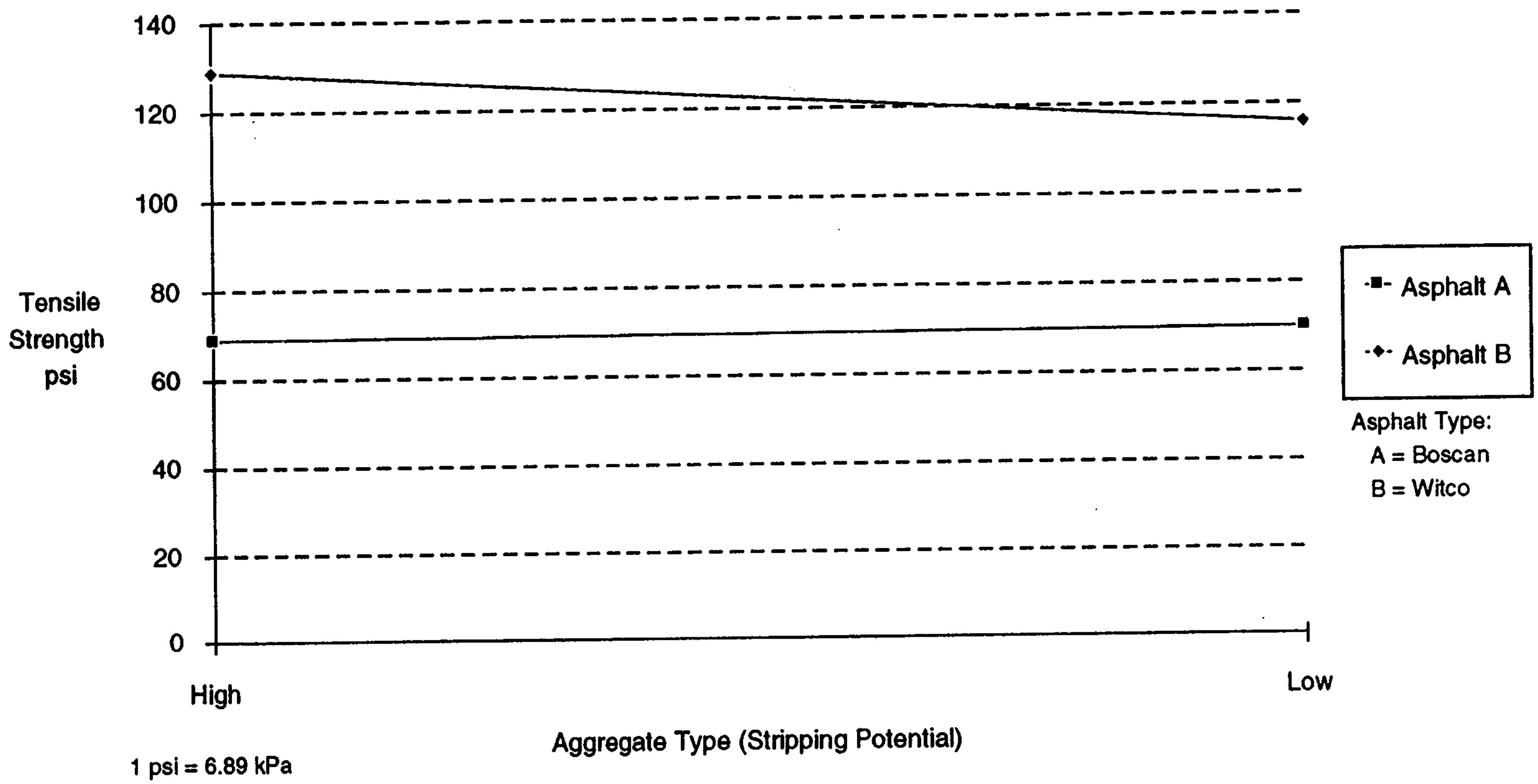


Figure 48. Effect of asphalt & aggregate type on tensile strength (77 °F [25 °C]).

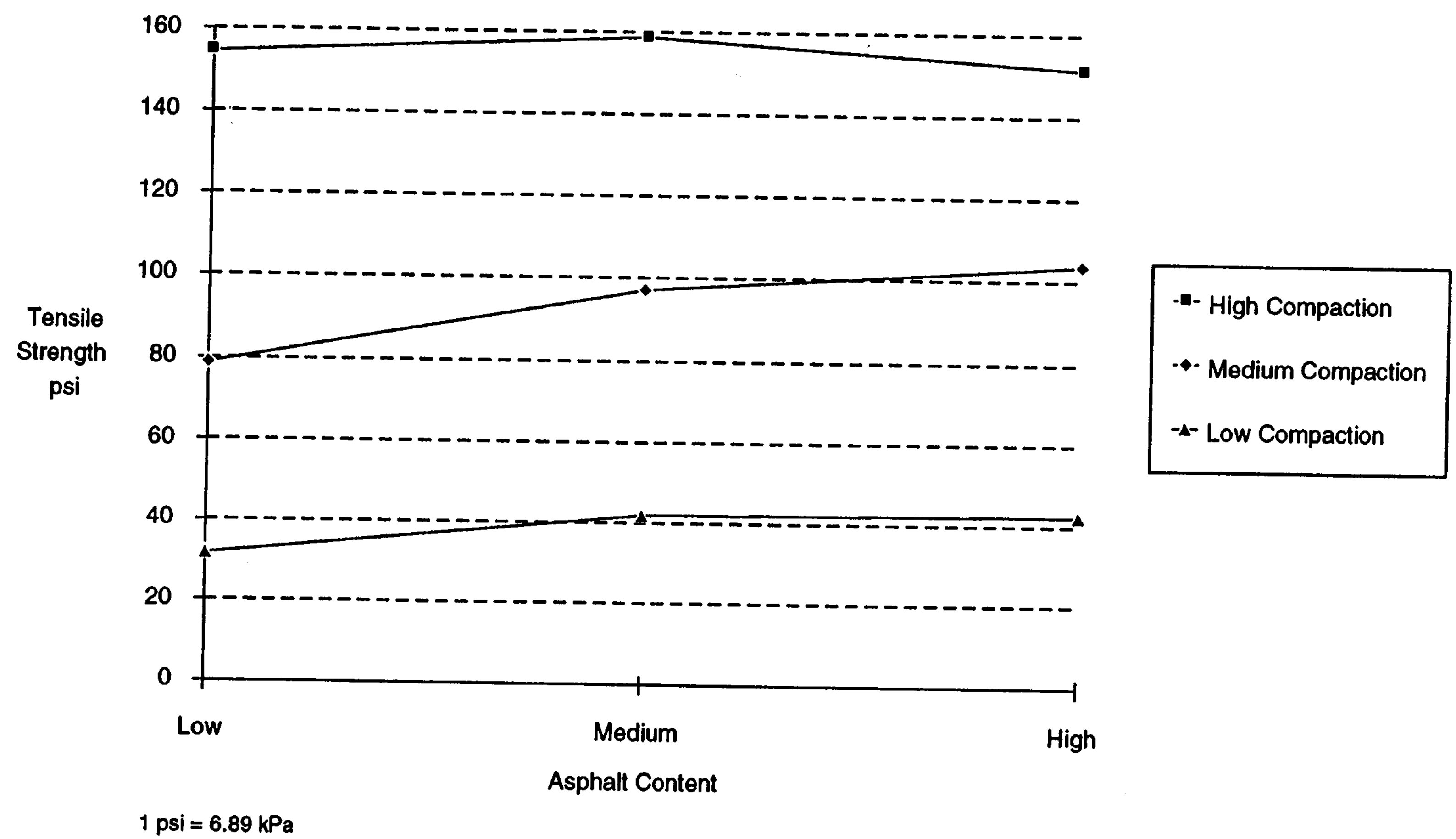


Figure 49. Effect of compaction & asphalt content on tensile strength (77 °F [25 °C]).

Table 39. Resilient modulus (ksi) mean values by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction			LOW				MEDIUM				HIGH				
Subtotal					Low Compaction				Medium Compaction				High Compaction		Row Totals
% Asphalt			-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	
Percent Passing Sieve #200	12.5	x =	85.0	115.3	95.6	94.8	225.4	196.3	389.2	225.4	526.9	497.4	446.5	489.8	283.9
		s =	48.1	59.8	49.7	48.7	56.0	33.1	193.2	56.0	383.9	205.9	291.2	290.5	259.8
		n =	7	3	8	18	4	2	3	4	6	5	6	17	44
	7.1		70.3	121.0	205.1	132.1	137.3	284.3	265.9	247.5	525.5	813.3	294.3	474.8	281.4
			29.1	65.0	112.9	89.1	0.0	0.0	138.8	120.5	268.0	0.0	228.2	278.4	232.1
			3	3	3	9	1	1	4	6	4	1	3	8	23
	2.1		68.2	83.8	64.5	68.5	187.8	256.2	230.3	219.5	318.6	332.3	299.5	313.9	196.0
			35.5	51.9	39.0	36.4	87.1	198.0	132.9	114.0	209.0	96.1	200.9	175.2	166.4
			8	2	7	17	3	2	2	7	6	4	7	17	41
Column Totals			75.1	109.6	101.8	92.3	200.3	237.8	299.1	249.2	448.4	463.0	353.7	415.8	250.1
			38.7	53.6	74.4	58.9	67.1	107.9	153.4	121.2	298.0	209.4	238.5	255.7	224.4
			18	8	18	44	8	5	9	22	16	10	16	42	108

x = Mean value
s = Standard deviation
n = Number cases

1 ksi = 6.89 kPa

Table 40. Tensile strength (psi) mean values by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction		LOW				MEDIUM				HIGH				
Subtotal		Low Compaction				Medium Compaction				High Compaction				Row
% Asphalt		-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	Totals
Percent Passing Sieve #200	12.5	x = 27.3 s = 9.8 n = 7	36.7 16.0 2	43.0 12.5 8	35.8 13.3 17	74.9 30.3 4	97.1 17.7 2	127.6 49.6 3	97.4 39.9 9	146.4 55.9 6	180.9 60.7 5	160.8 59.5 6	161.6 56.6 17	98.4 69.3 43
	7.1	32.4 11.2 3	47.3 15.0 3	53.7 20.9 3	44.4 16.9 9	54.2 0.0 1	115.1 0.0 1	90.6 14.0 4	88.6 22.3 6	198.7 88.5 4	240.4 0.0 1	155.9 72.6 3	187.9 75.9 8	105.8 78.2 23
	2.1	34.8 13.4 8	39.5 17.3 2	36.6 12.9 7	36.1 12.7 17	91.1 23.6 3	88.8 36.3 2	94.8 58.3 2	91.5 31.3 7	132.9 49.3 6	110.4 43.9 4	141.1 58.5 7	130.9 50.6 17	84.9 56.2 41
Column Totals		31.5 11.6 18	42.0 13.9 7	42.3 14.5 18	37.7 14.0 43	78.4 26.7 8	97.3 22.9 5	103.8 37.9 9	93.1 31.9 22	154.4 64.5 16	158.6 65.8 10	151.3 57.8 16	154.2 60.8 42	94.8 66.6 107

x = Mean value
s = Standard deviation
n = Number cases

1 psi = 6.89 kPa

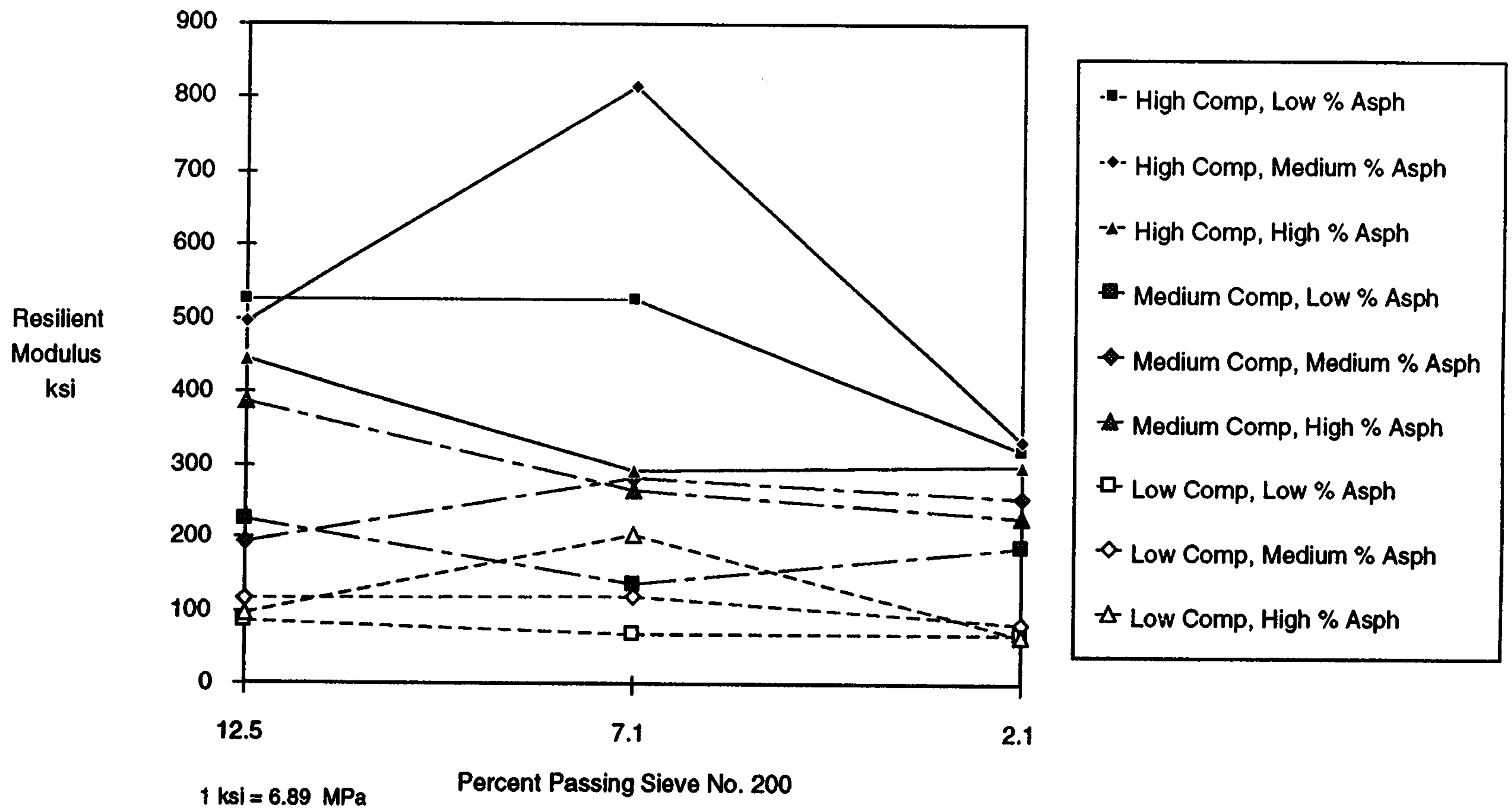


Figure 50. Effect of sieve No. 200 (75 μm) on resilient modulus (77 °F [25 °C]).

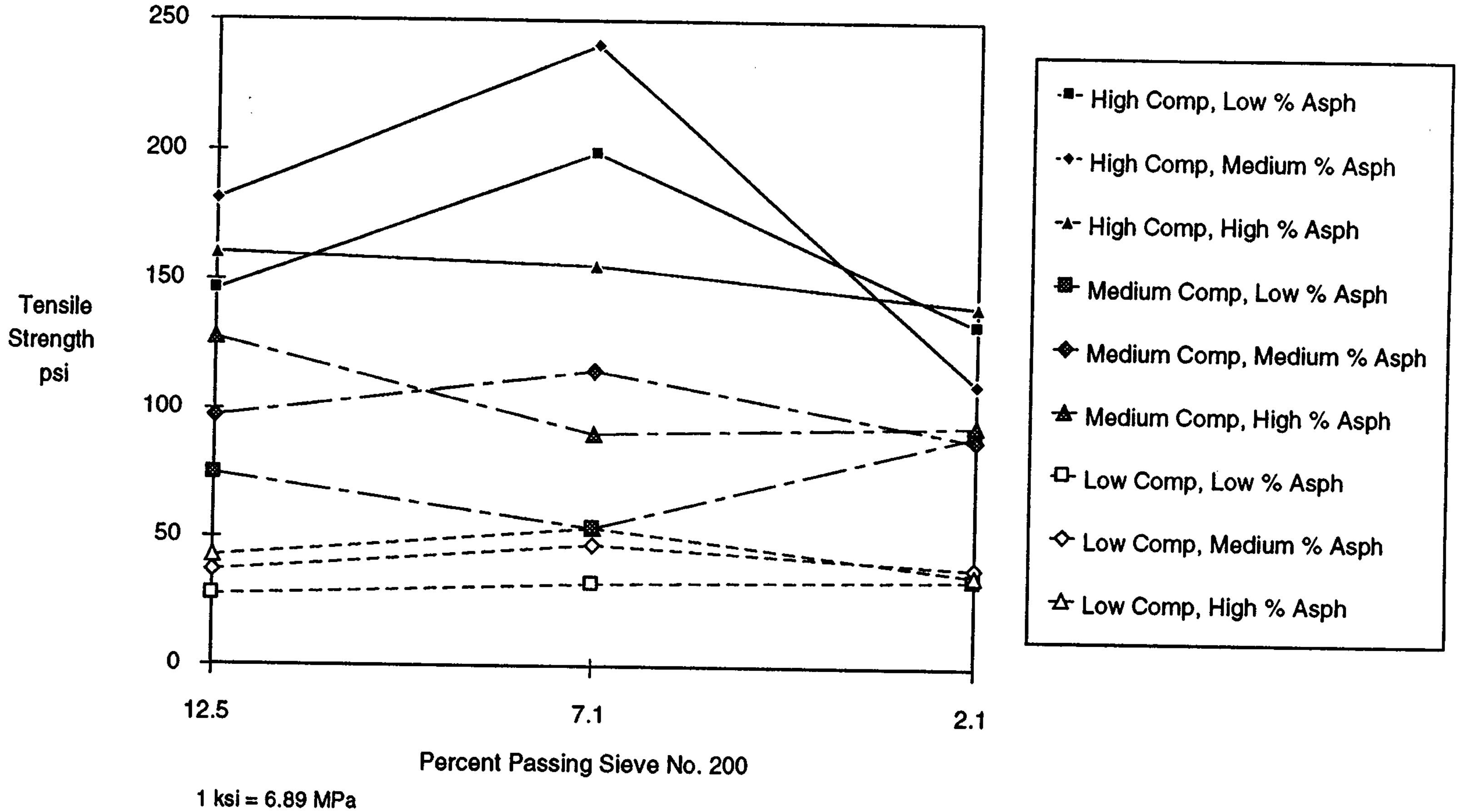


Figure 51. Effect of sieve No. 200 (75 µm) on tensile strength (77 °F [25 °C]).

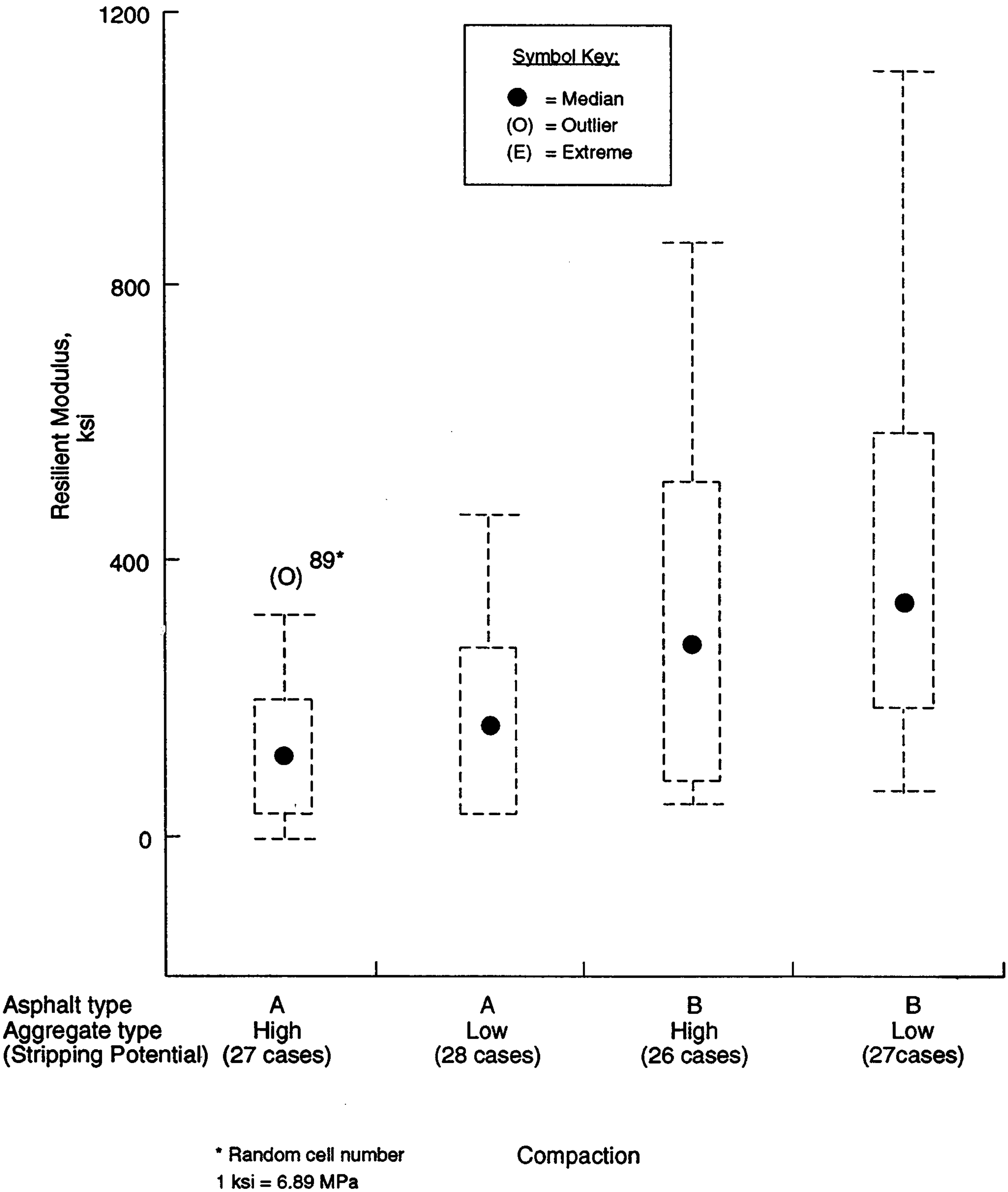


Figure 52. Distribution of resilient modulus values by asphalt type and aggregate type.

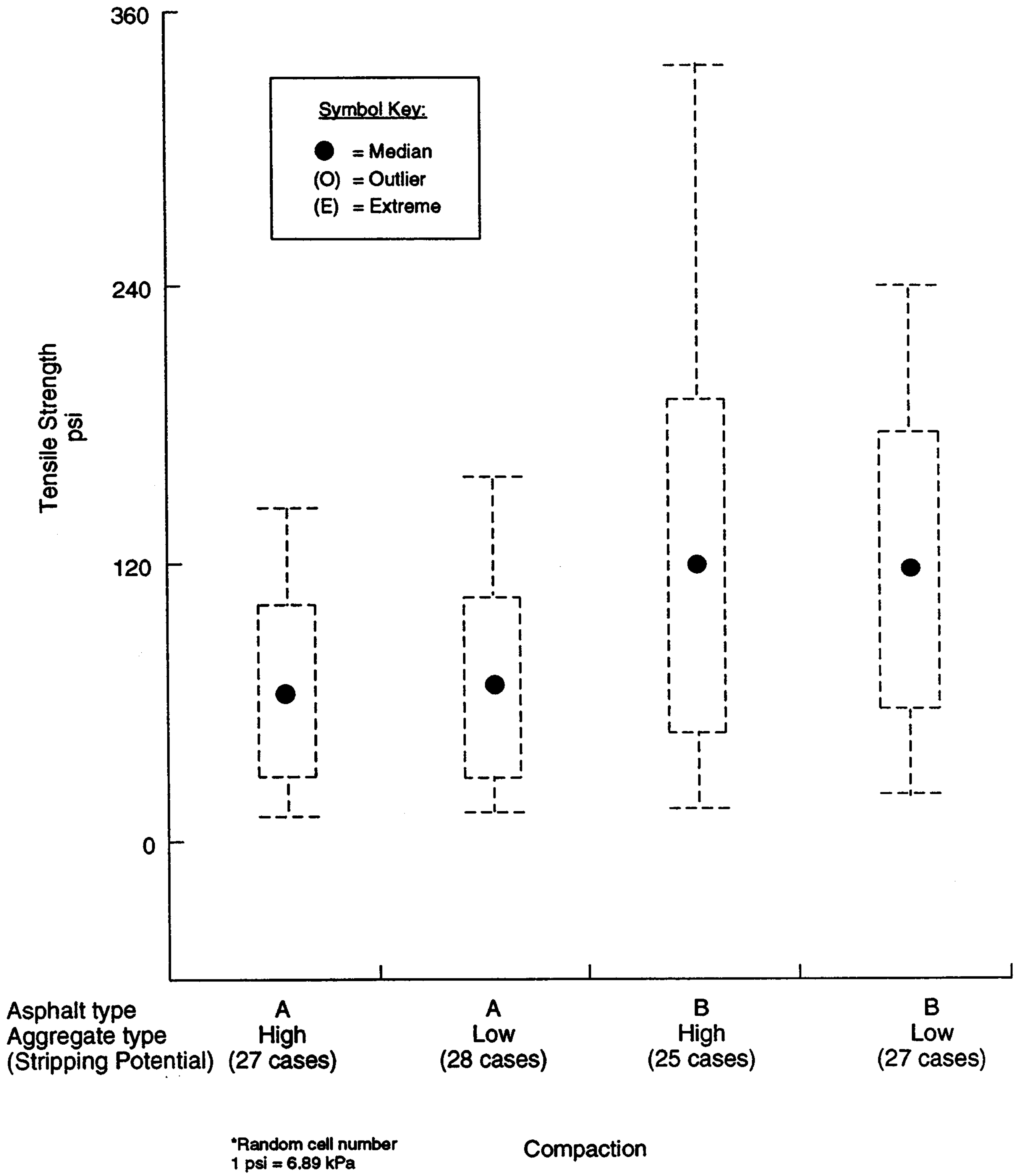


Figure 53. Distribution of tensile strength values by asphalt type and aggregate type.

Mean values for the AGMRR are shown in table 41 with figure 54 as the corresponding plot. The interesting trend for these values is that samples at low compaction level have in general gained more strength with time than corresponding samples at high and medium compaction levels. Also, there is a nonlinear effect of the percent passing sieve No. 200 (75 μm) for most combinations of percent asphalt content and compaction level. Mean values for the AGTSR (table 42 and figure 55) show similar trends as already described for AGMRR.

The effect of percent passing sieve No. 200 (75 μm) on the strength of moisture-conditioned samples is shown in table 43 and figure 56 for the resilient modulus, and in table 44 and figure 57 for the tensile strength. No trends other than a nonlinear effect of the sieve No. 200 (75 μm) were observed.

The effect of different materials and construction variables on air voids is presented in figure 58. The mean values used to generate these plots are summarized in table 45. As expected, the percent air voids decreases as compaction effort increases. It also decreases as the percent asphalt content increases. Percent air voids is more sensitive to a change in the percent passing sieve No. 30 (600 μm) between the low and medium percents than a change between the medium and high percents. The effect of the percent passing sieve No. 200 (75 μm) on air voids seems to be nonlinear according to these test results.

A box plot showing the range of percent air voids for each compaction level is shown in figure 59. The percent air voids for the low compaction level varies from 3.0 to 18.5 with a mean value of 11.9. The range for the medium compaction level is from 2.8 to 12.6 with a mean value of 7.2. The high level compaction varies from 0.2 to 17.5 percent air voids. This includes an outlier and an extreme value corresponding to samples 5 and 13. The mean value for this compaction level was 4.5.

Spread level plots to study the effect of air voids on resilient modulus are presented in figures 60 through 64. Figure 60 is for all samples while figures 61 through 64 represent different combinations of asphalt and aggregate type. From figure 60 there is more variability in resilient modulus for a percent air voids less than 8 to 10 percent than at higher air voids. Variables other than air voids are therefore more important in predicting resilient modulus for percent air voids less than 8 to 10 percent. Air voids may be one of the most important variables in explaining the consistently low resilient modulus values for percent air voids above 8 to 10 percent.

Figures 61 through 64 show more variability in resilient modulus for the asphalt with high temperature susceptibility than for the asphalt with low temperature susceptibility. In all cases the transition at the 8 to 10 percent air voids is present.

Linear Regression Analyses. A regression model is a mathematical expression for a relationship between a given dependent variable (Y) and both explicit independent variables (X1, X2, ...) and undefined variables whose net effects produce unexplained (error) variation in Y. The regression models for this study have been limited to multilinear regression

Table 41. Aged resilient modulus ratio mean values by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction			LOW				MEDIUM				HIGH				
Subtotal						Low Compaction				Medium Compaction				High Compaction	Row Totals
% Asphalt			-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	
Percent Passing Sieve #200	12.5	x =	3.32	3.93	2.95	3.29	2.85	2.86	1.98	2.56	2.16	1.82	1.74	1.89	2.57
		s =	1.21	1.40	0.51	1.02	0.48	0.23	0.22	0.54	0.64	0.66	0.40	0.56	0.97
		n =	6	3	6	15	4	2	3	9	5	5	6	16	40
	7.10		4.71	4.06	1.73	3.89	1.42	1.89	1.32	1.43	1.71	2.00	1.67	1.73	2.29
			1.47	2.58	0.00	2.08	0.00	0.00	0.14	0.25	0.32	0.00	0.41	0.32	1.54
			2	3	1	6	1	1	4	6	4	1	3	8	20
	2.10		3.75	1.61	4.00	3.70	2.32	1.79	1.43	1.75	1.84	1.71	1.33	1.62	2.47
			2.71	0.00	1.86	2.26	0.00	0.40	0.25	0.43	0.59	0.40	0.33	0.49	1.78
			7	1	6	14	1	2	2	5	6	4	6	16	35
Column Totals			3.71	3.65	3.34	3.56	2.52	2.24	1.56	2.02	1.91	1.79	1.56	1.75	2.47
			2.00	1.92	1.44	1.75	0.69	0.61	0.35	0.67	0.55	0.50	0.40	0.50	1.42
			15	7	13	35	6	5	9	20	15	10	15	40	95

x = Mean value
s = Standard deviation
n = Number cases

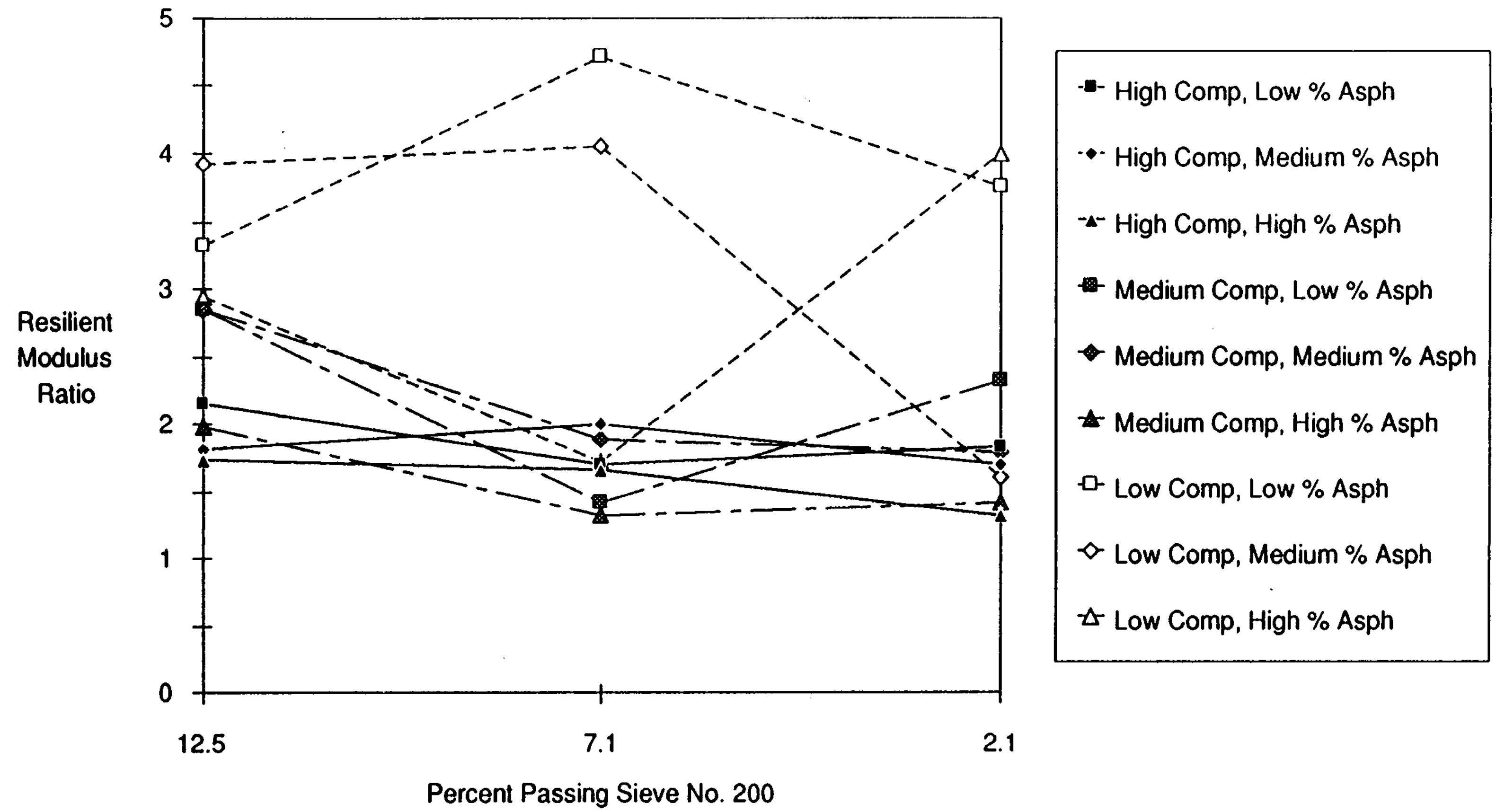


Figure 54. Effect of sieve No. 200 (75 μm) on resilient modulus of aged samples.

Table 42. Aged tensile strength ratio mean values by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction		LOW				MEDIUM				HIGH				
Subtotal		Low Compaction				Medium Compaction				High Compaction				Row
% Asphalt		-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	Totals
Percent Passing Sieve #200	12.5	x = 1.77	2.18	1.78	1.83	1.84	1.18	1.30	1.51	1.30	1.36	1.19	1.27	1.54
		s = 0.44	0.18	0.43	0.41	0.75	0.05	0.09	0.56	0.18	0.28	0.14	0.20	0.45
		n = 6	2	6	14	4	2	3	9	5	4	6	15	38
	7.10	2.09	2.31	2.06	2.20	1.26	1.19	1.55	1.44	1.34	1.16	1.07	1.22	1.58
		0.69	0.20	0.00	0.36	0.00	0.00	0.50	0.42	0.39	0.00	0.15	0.30	0.54
		2	3	1	6	1	1	4	6	4	1	3	8	20
	2.10	1.96	1.27	2.06	1.90	1.46	1.51	1.45	1.48	1.25	2.14	1.18	1.45	1.63
		0.84	0.13	0.49	0.66	0.00	0.03	0.10	0.06	0.29	1.61	0.30	0.87	0.74
		6	2	6	14	1	2	2	5	6	4	6	16	35
Column Totals		1.90	1.98	1.93	1.93	1.68	1.32	1.44	1.48	1.29	1.68	1.16	1.33	1.58
		0.63	0.51	0.44	0.53	0.64	0.18	0.33	0.43	0.27	1.09	0.21	0.58	0.59
		14	7	13	34	6	5	9	20	15	9	15	39	93

x = Mean value
s = Standard deviation
n = Number cases

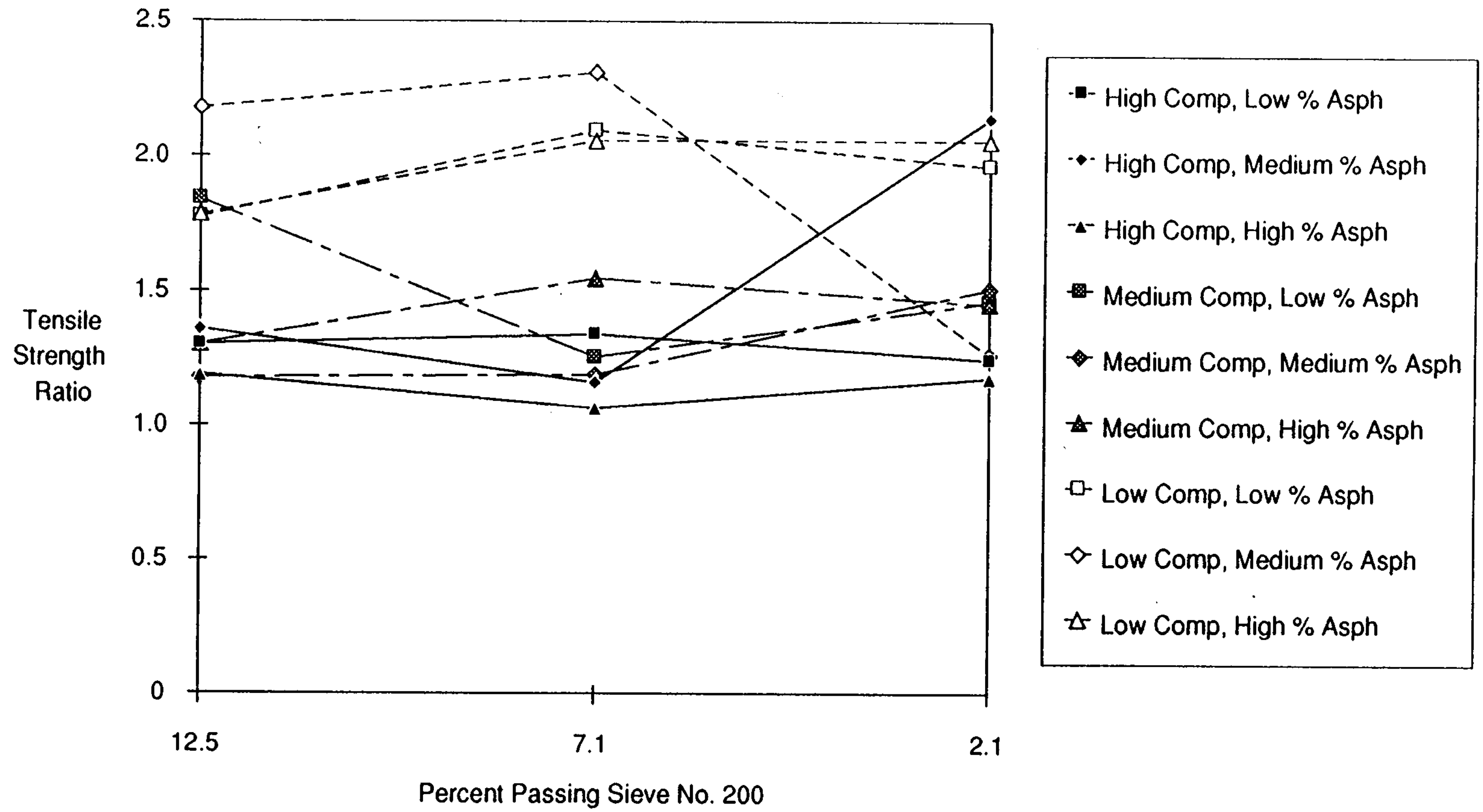


Figure 55. Effect of sieve No. 200 (75 μm) on tensile strength of aged samples.

Table 43. Mean values for the index of retained modulus by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction			LOW				MEDIUM				HIGH				
Subtotal					Low Compaction				Medium Compaction				High Compaction	Row
% Asphalt		-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	Totals
Percent Passing Sieve #200	12.5	x = 77.1	61.8	83.7	77.2	82.7	70.2	71.6	76.2	77.4	84.1	66.3	74.9	76.1
		s = 34.9	39.1	33.5	33.6	43.9	84.7	13.7	41.3	35.6	44.5	28.3	33.8	34.5
		n = 6	3	7	16	4	2	3	9	6	4	6	16	41
	7.1	78.2	109.1	79.8	89.0	54.1	113.8	71.0	75.3	87.4	101.7	89.0	89.8	85.2
		5.0	8.7	11.8	17.0	0.0	0.0	27.3	29.2	19.9	0.0	15.0	16.1	21.0
		2	2	2	6	1	1	4	6	3	1	4	8	20
	2.1	96.4	53.7	92.4	88.0	125.2	44.4	66.3	85.3	62.0	92.1	107.8	87.9	87.4
		35.4	34.6	29.1	34.2	81.9	9.8	6.2	61.1	42.4	30.1	42.0	42.7	42.9
		6	2	4	12	3	2	2	7	6	4	7	17	36
Column Totals		85.6	73.0	85.8	83.1	95.1	68.6	70.2	78.9	74.1	89.7	88.7	83.2	82.2
		32.4	36.6	28.4	31.3	58.8	51.2	18.3	44.0	34.8	33.4	37.0	35.3	35.8
		14	7	13	34	8	5	9	22	16	9	16	41	97

x = Mean value
s = Standard deviation
n = Number cases

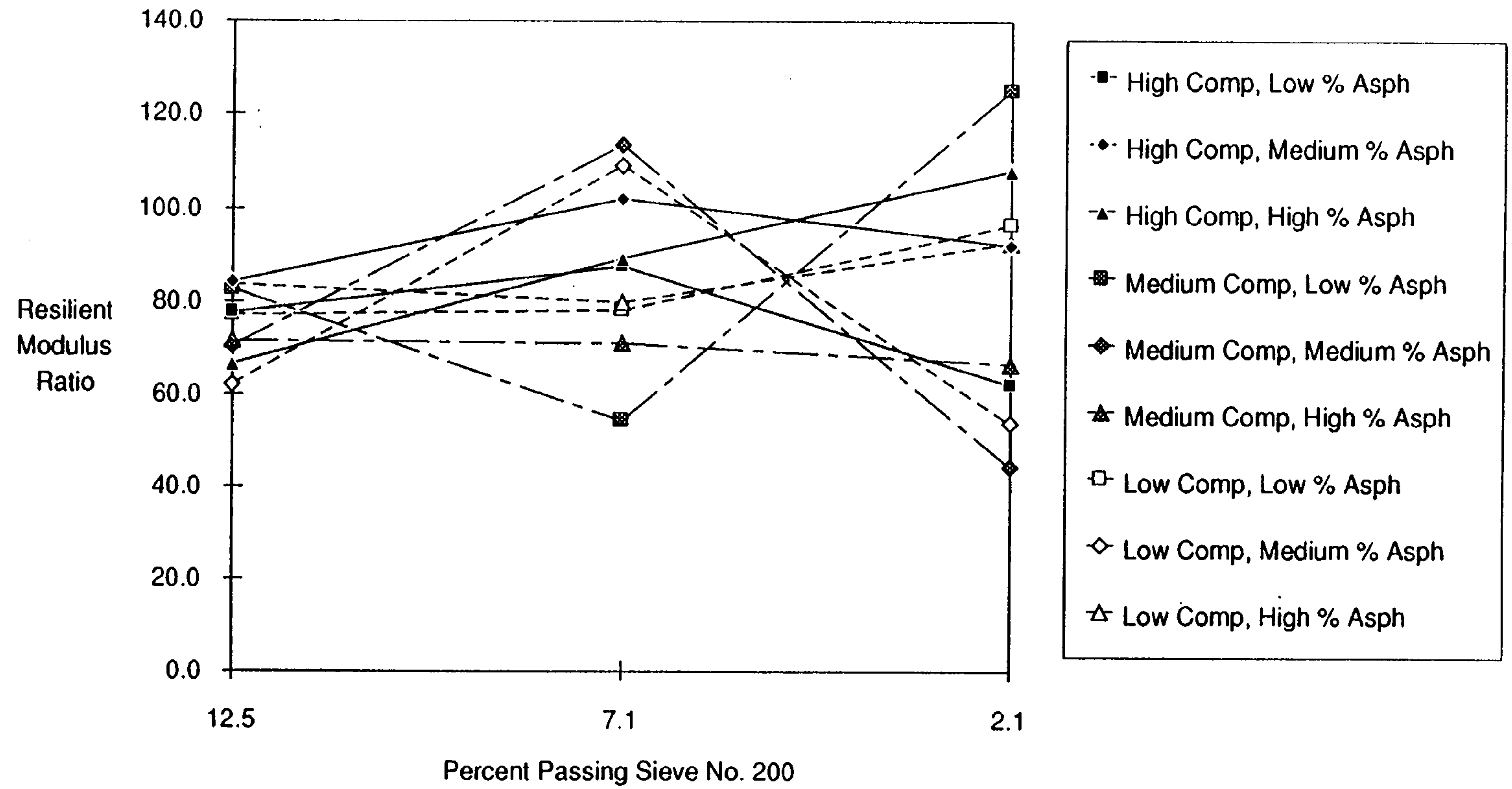


Figure 56. Effect of sieve No. 200 (75 μm) on resilient modulus of moisture-conditioned samples.

Table 44. Mean values for the index of retained strength by compaction level, by percent asphalt content, and by percent passing sieve #200 (75 μm).

Compaction		LOW				MEDIUM				HIGH				
Subtotal					Low Compaction				Medium Compaction				High Compaction	Row
% Asphalt		-0.75	0	0.75	Total	-0.75	0	0.75	Total	-0.75	0	0.75	Total	Totals
Percent Passing Sieve #200	12.5	x = 89.9 s = 31.5 n = 6	72.1 27.4 2	80.2 23.6 7	83.0 26.2 15	120.1 64.8 4	54.4 51.6 2	78.7 22.1 3	91.7 53.3 9	72.4 27.7 6	57.0 30.4 3	75.8 14.1 6	70.6 23.0 15	80.3 33.4 39
	7.1	60.2 34.8 3	97.3 1.5 2	64.5 17.7 2	72.0 27.5 7	85.8 0.0 1	88.5 0.0 1	61.6 33.5 4	70.1 29.1 6	64.7 37.7 4	103.6 0.0 1	82.3 12.2 3	76.2 29.1 8	73.1 27.3 21
	2.1	131.6 100.8 6	63.7 29.4 2	82.6 18.6 5	102.3 72.5 13	103.8 53.4 3	55.8 0.7 2	77.2 15.6 2	82.5 38.3 7	72.3 45.2 6	140.9 107.7 4	83.7 25.1 6	94.0 63.4 16	94.8 61.9 36
Column Totals		100.7 70.5 15	77.7 23.5 6	78.8 20.6 14	88.0 49.2 35	109.7 52.6 8	61.8 29.8 5	70.7 25.5 9	82.9 42.2 22	70.7 35.1 16	104.8 83.4 8	80.3 18.2 15	81.4 45.3 39	84.1 45.7 96

x = Mean value
s = Standard deviation
n = Number cases

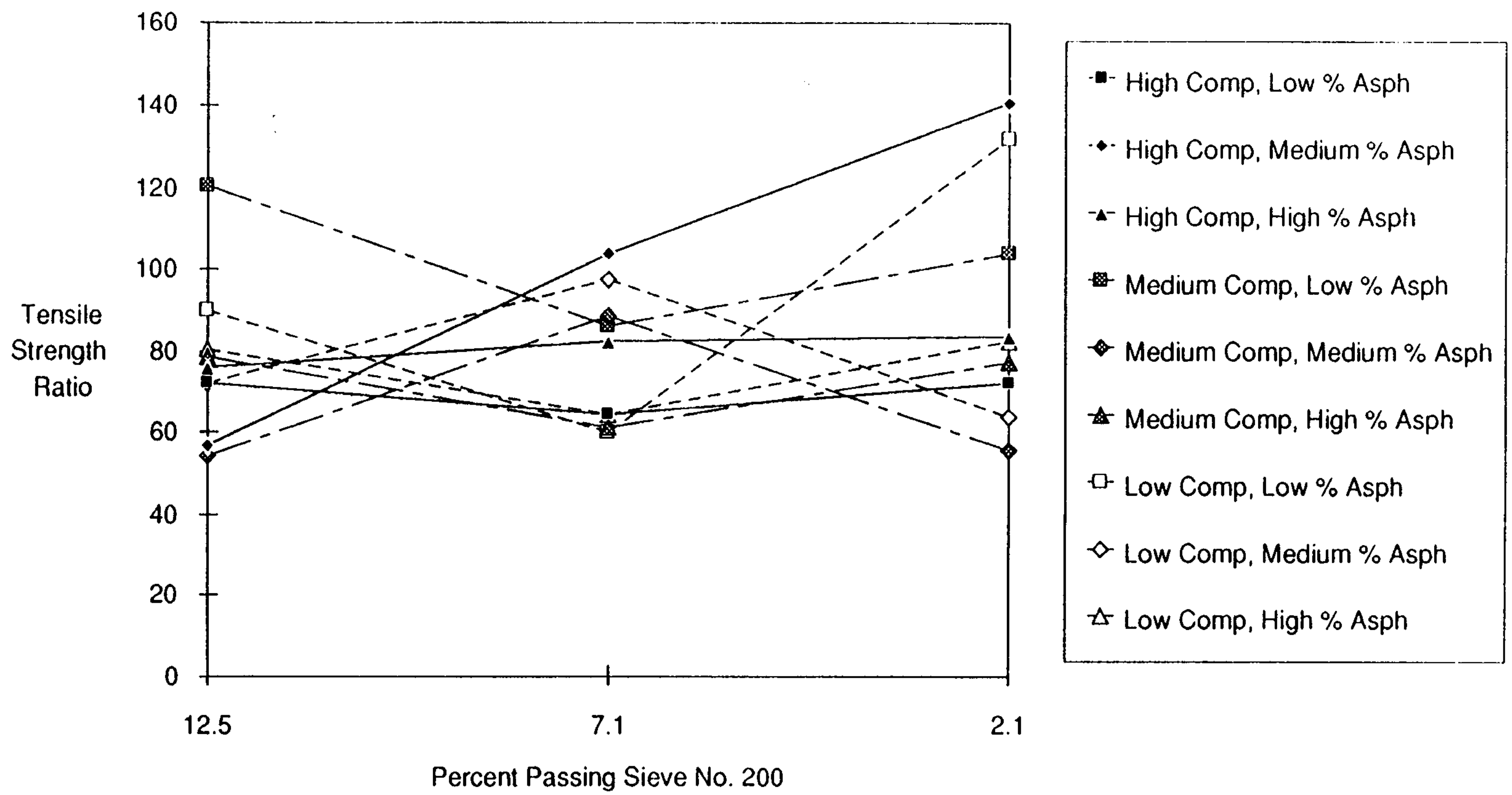
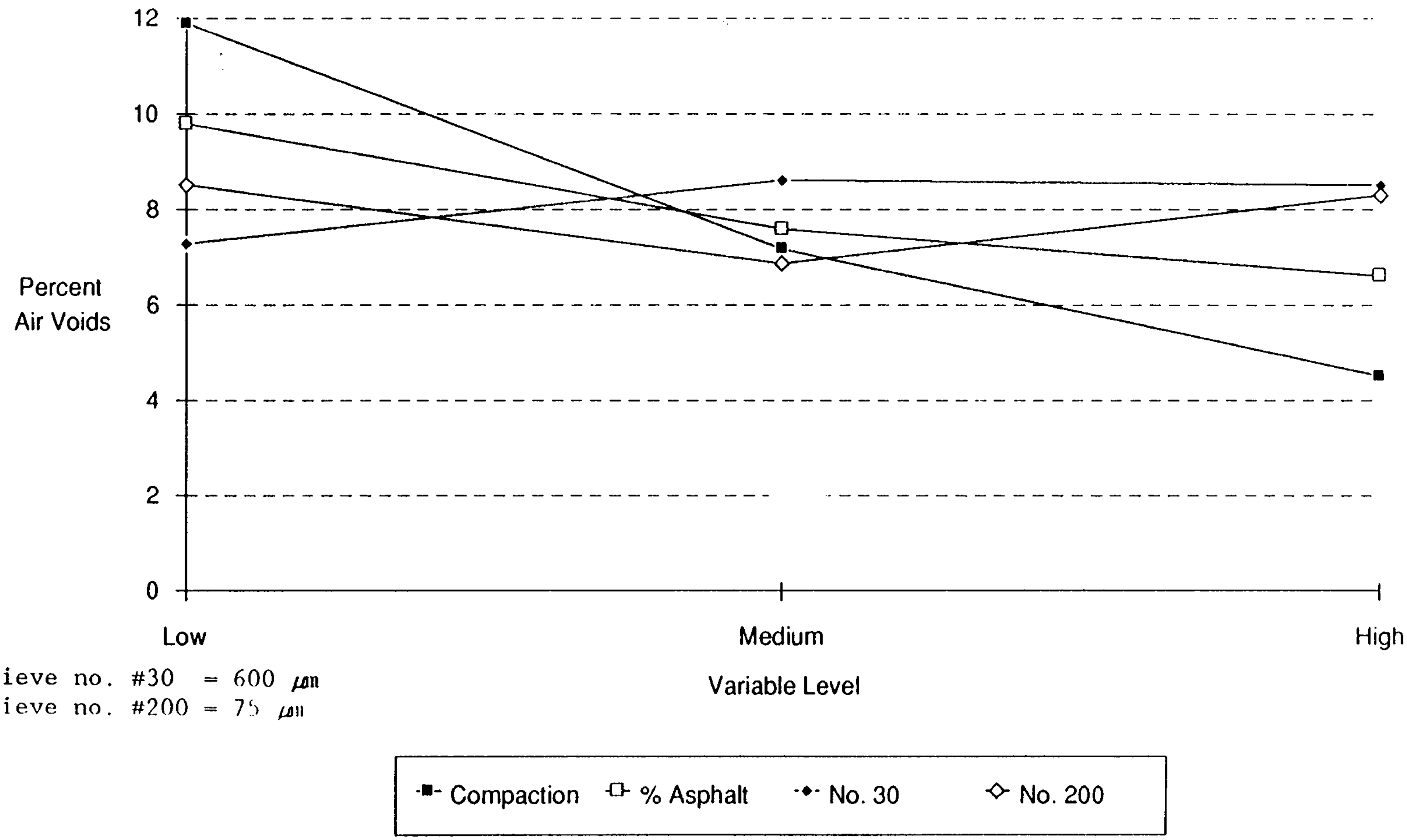


Figure 57. Effect of sieve No. 200 (75 μm) on tensile strength of moisture-conditioned samples.



sieve no. #30 = 600 μm
sieve no. #200 = 75 μm

Figure 58. Effect of M&C variables on air voids.

Table 45. Effect of M&C variables on air voids.

		Low	Medium	High	
Compaction		Low	Medium	High	
	x =	11.9	7.2	4.5	
	s =	2.9	2.7	3.2	
	n =	44	22	42	
Percent Asphalt		-0.75	0	0.75	
		9.8	7.6	6.6	
		4.4	4.0	4.2	
		42	23	43	
Percent Passing Sieve #30		13.0	18.1	30.4	
		7.3	8.6	8.5	
		3.6	4.8	5.0	
		43	24	41	
Percent Passing Sieve #200		2.1	7.1	12.5	
		8.5	6.9	8.3	
		4.4	4.6	4.4	
		41	23	44	
Entire Population					8.1
					4.5
					108

x = Mean value
s = Standard deviation
n = Number of cases

sieve no. #30 = 600 μm
sieve no. #200 = 75 μm

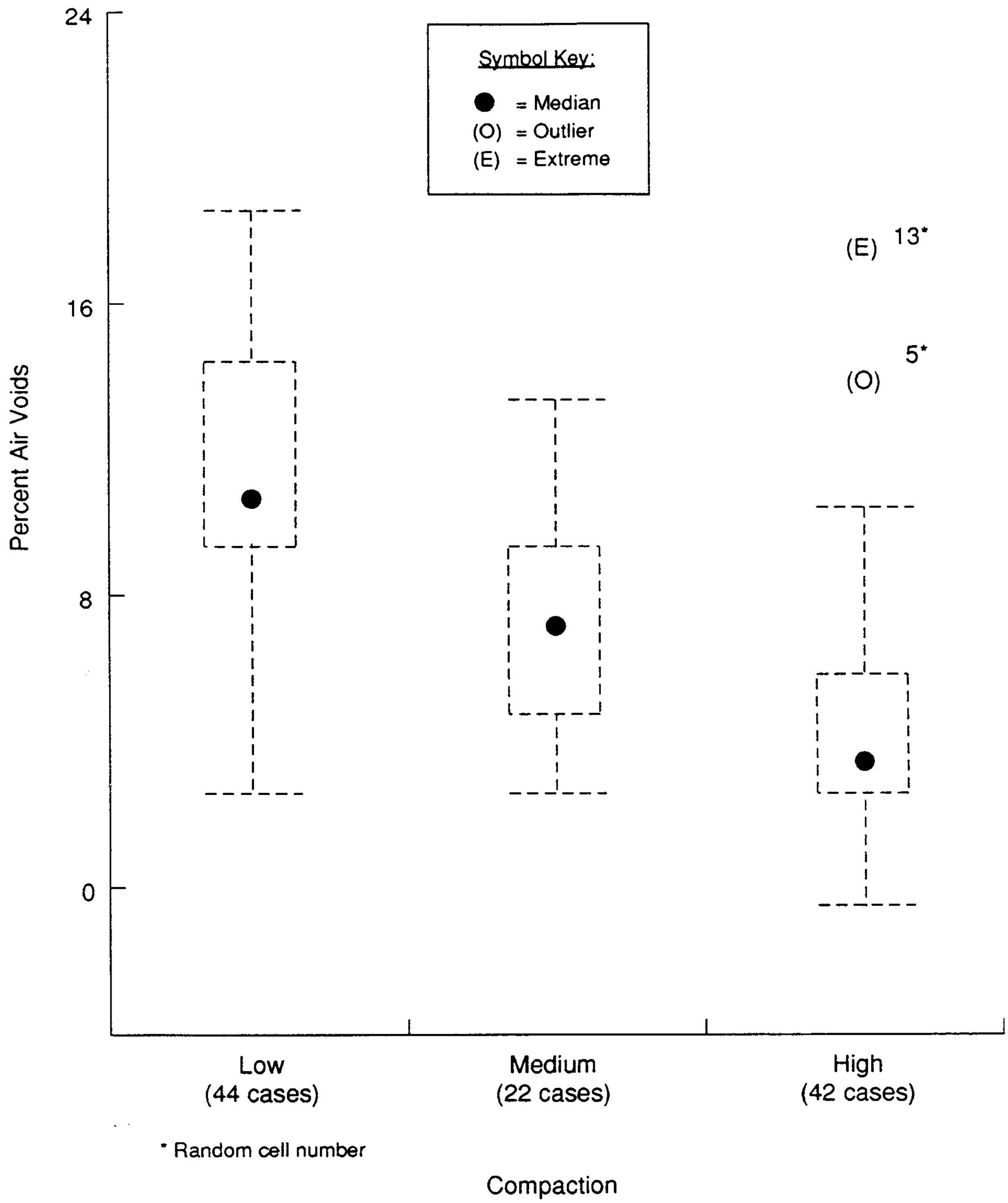


Figure 59. Distribution of percent air voids by compaction level.

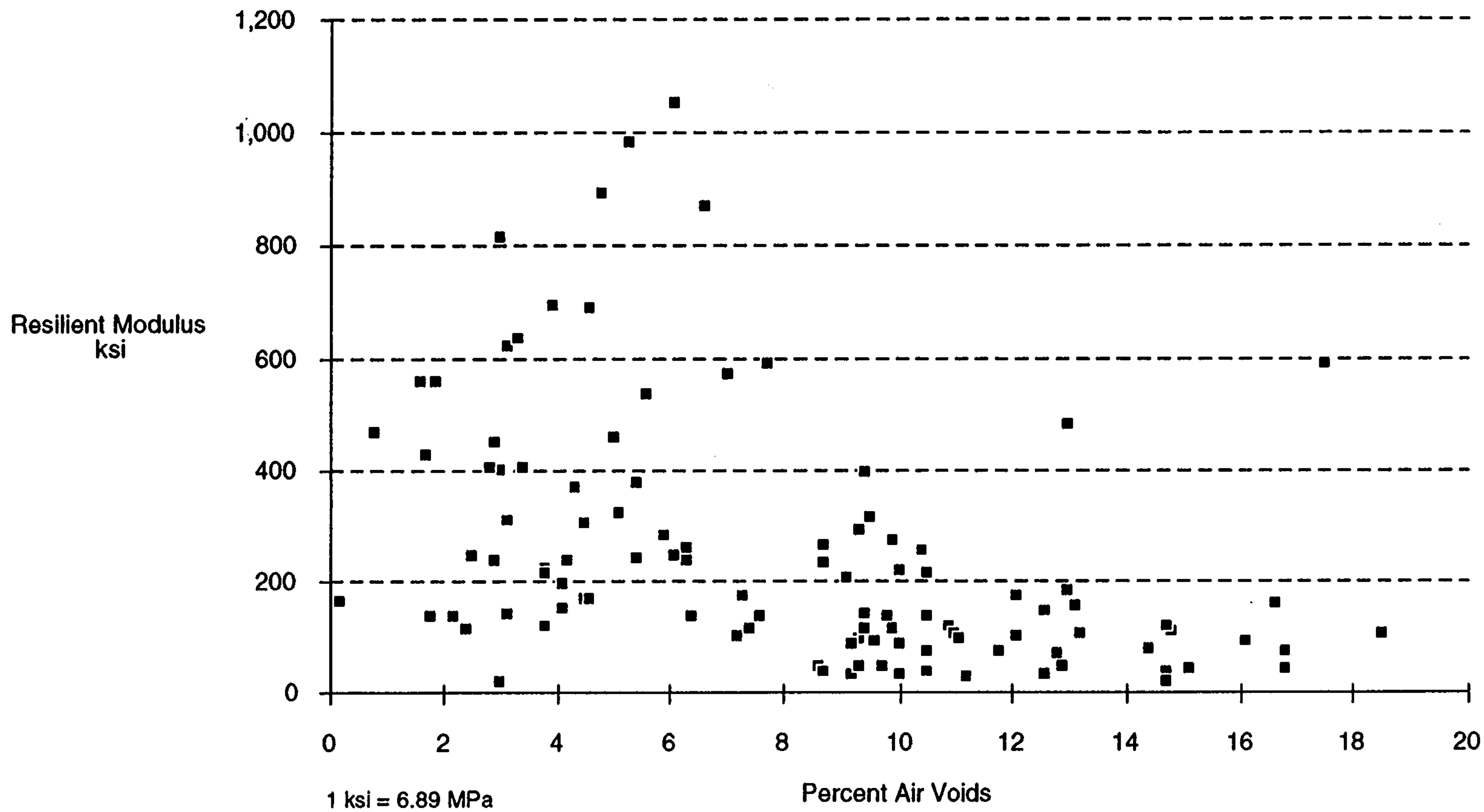


Figure 60. Effect of percent air voids on resilient modulus at 77 °F (25 °C) for all samples.

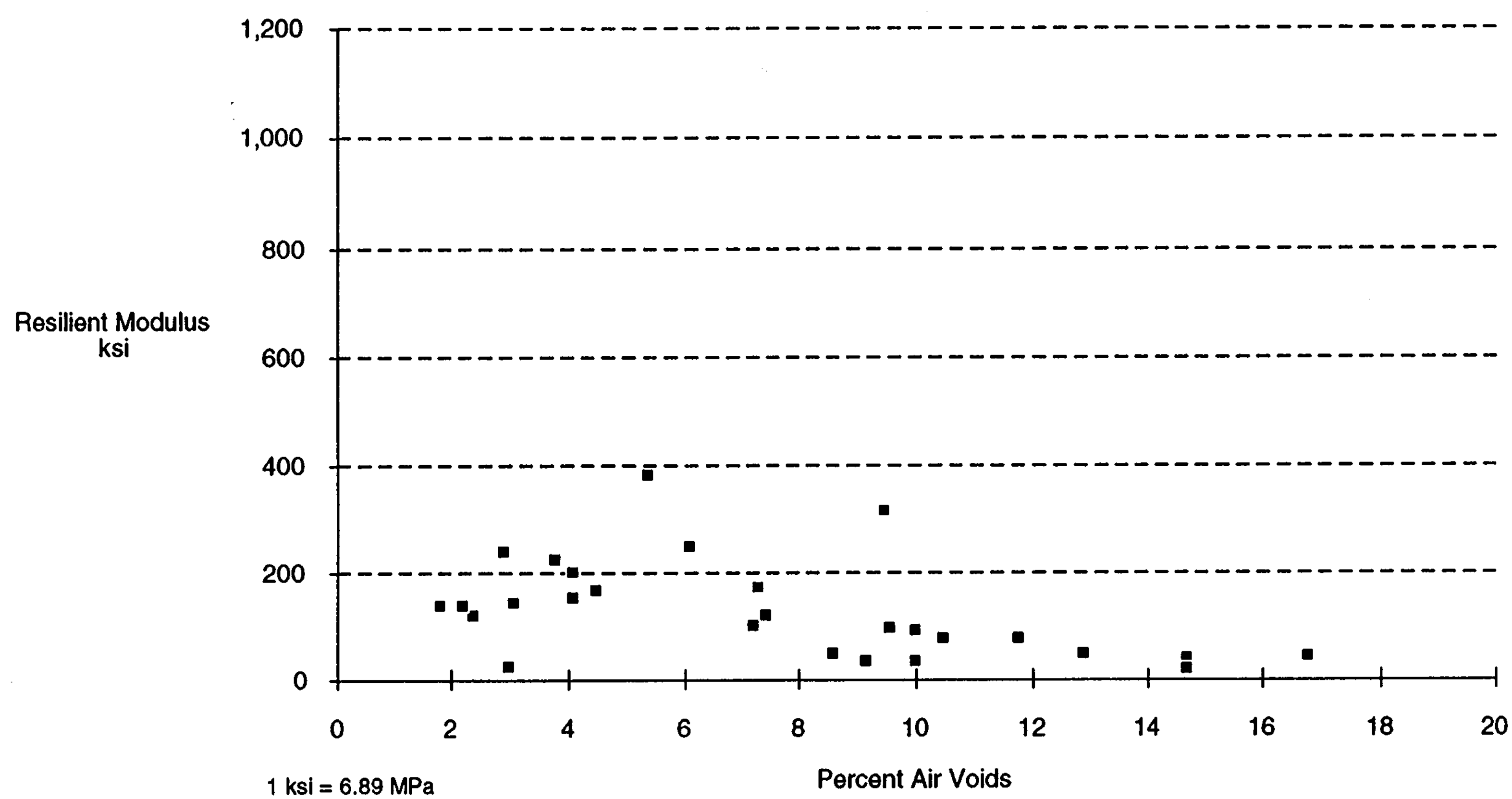


Figure 61. Effect of percent air voids on resilient modulus at 77 °F (25 °C) for samples with low stripping potential and low temperature susceptibility.

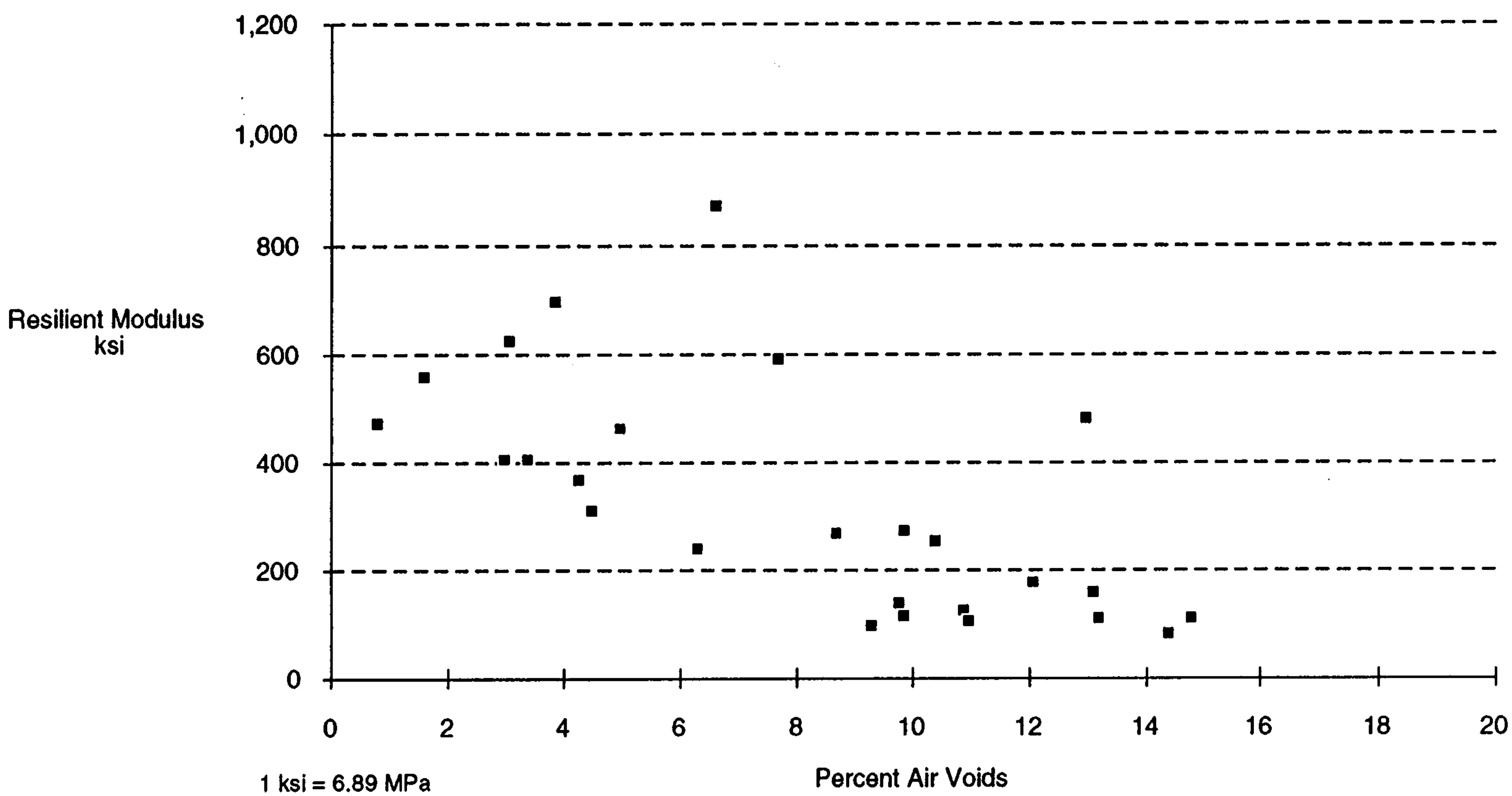


Figure 62. Effect of percent air voids on resilient modulus at 77 °F (25 °C) for samples with low stripping potential and high temperature susceptibility.

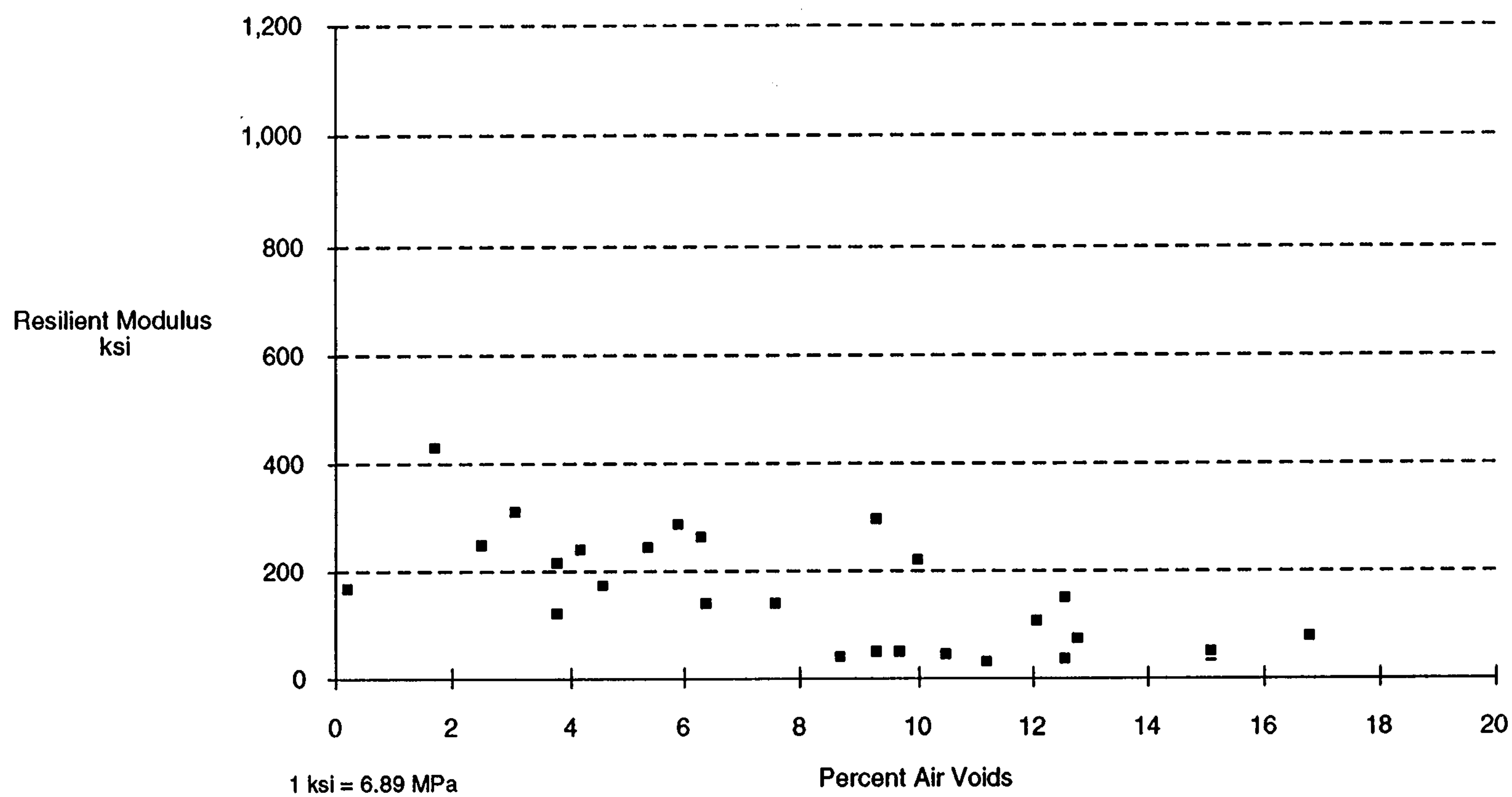


Figure 63. Effect of percent air voids on resilient modulus at 77 °F (25 °C) for samples with high stripping potential and low temperature susceptibility.

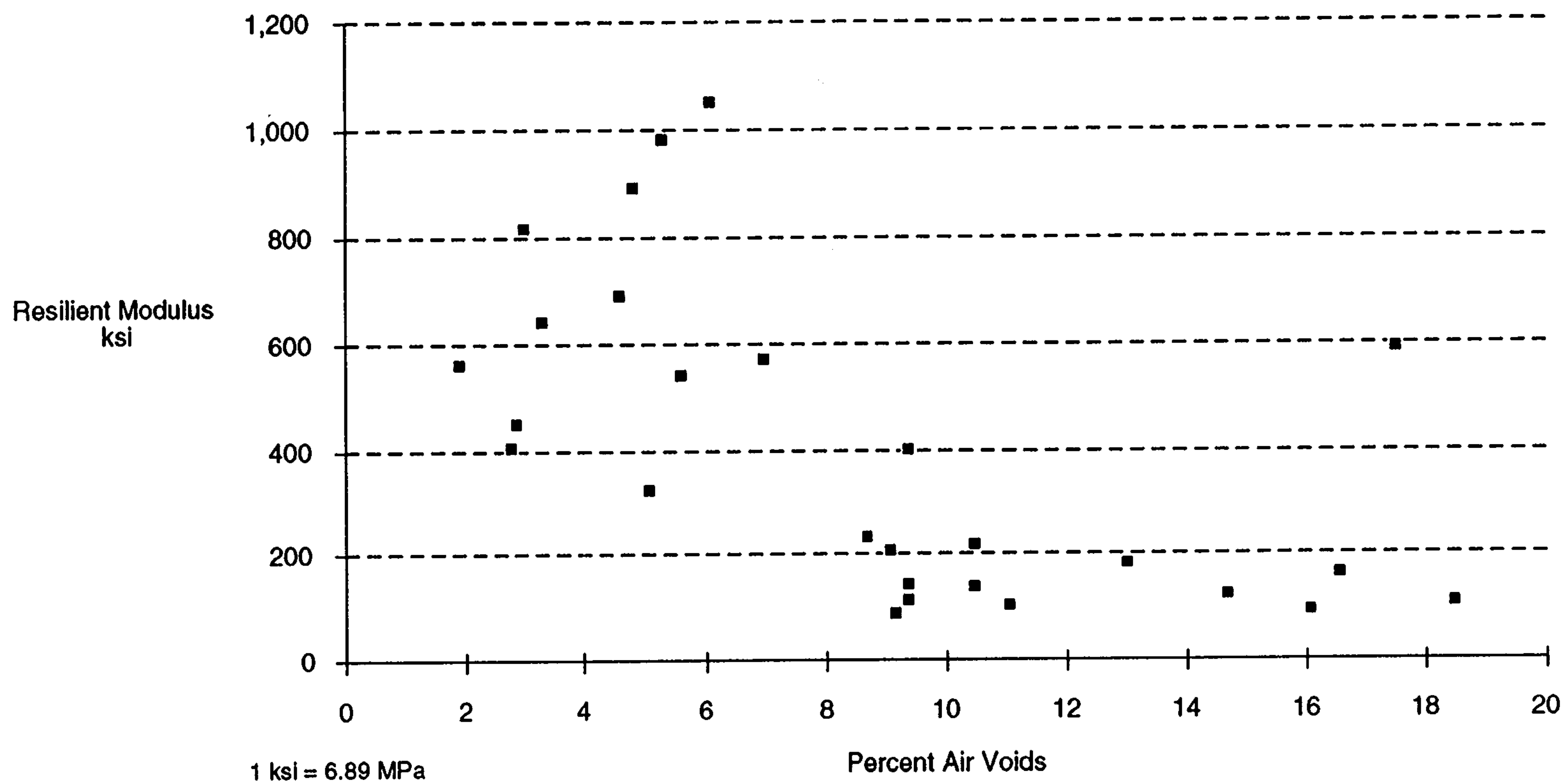


Figure 64. Effect of percent air voids on resilient modulus at 77 °F (25 °C) for samples with high stripping potential and high temperature susceptibility.

analyses (i.e., Y values are predicted by a linear combination of X variables). It is assumed that repeated observations of Y for fixed values of the independent variables would produce independent residuals that have a normal frequency distribution with a mean value of zero (i.e., unbiased predictions) and a standard deviation of SSE, the standard error of the equation predictions.

All multiple regression analyses included in this appendix used as inputs the values in table 32. Each regression run gives one regression equation and produces from 10 to 40 pages of printout. The regression run summary, table 46, has been developed to bring important results of the printout pages for each run into a single table. Each table contains the following results:

EQ:	A sequence number for equations generated for each dependent variable.
N:	The number of cases (rows) that were used for regression inputs.
VARIABLES:	Field names for one dependent variable (Y) and up to 12 independent variables (X1, X2,...)
MEAN AND SD:	The mean and standard deviation of each regression variable. These values often serve to indicate gross errors in input data and can be used to center independent variables around their mean values.
CORR YX:	Correlation coefficients for linear associations of Y with each X. They help to forecast the relative importance of X's.
CORR XX > 0.8:	Correlation coefficients between pairs of independent variables whose correlations may be high enough to impede both the regression analysis and interpretation of the regression equations.
B and SEB:	Regression coefficients (B) for X variables in the equation (including the constant term) and corresponding standard errors (SEB).
R^2:	Squared multiple correlation coefficient (or coefficient of determination). Equals the fraction of Y variance that is explained by X variables in the equations.
SSE:	Standard error of estimate. This is approximately equal to the standard deviation of the equation's residuals. (Note this quantity is referred to as SE in the main body of this report.)

Table 46. Blank form for regression run summaries.

Regression Summary for Run ______ . ___

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
										Statistic:	DF:	Significance:

VARIABLES	B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
									YX	XX>0.8	RDNUM	Y	PRED	Z RESID
Y														
CONSTANT														
X_1														
X_2														
X_3														
X_4														
X_5														
X_6														
X_7														
X_8														
X_9														
X_{10}														
X_{11}														
X_{12}														

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

STEP:	Number of steps (in the stepwise regression procedure) used to derive the final equations. COND BDS:Lower and upper bounds for the condition number of the independent variable matrix. Large values imply low stability and precision for regression coefficients, and arise because of multicollinearities among X variables.
COND BDS:	Lower and upper bounds for the condition number of the independent variable matrix. Large values imply low stability and precision for regression coefficients, and arise because of multicollinearities among X variables.
BETA:	Standardized regression coefficient that generally reflects the relative importance of X variables in the equation.
Partial:	Partial correlation coefficient that shows the correlation between Y and X_i when linear effects of all other X_j have been removed from both Y and X_i.
T and Sig:	T is the ratio (B/SEB) of a regression coefficient to its standard error. Sig indicates the probability for Bi under the hypothesis that its "population" value is zero. Sig is small for variables in the equation and large for variables not in the equation.
Residuals Statistics (Min Res and Max Res):	Tabulated values of minimum and maximum residual for predicted Y values.
DURBIN:	The value of the Durbin-Watson statistic for serial correlation of residuals. Serial correlation is indicated whenever the statistic is lower or greater than published criterion values.
Outliers:	Potential outliers are defined to be test values whose z residual exceeds 2.5 in absolute value. Outlier case numbers (RDNUM), corresponding Y value, predicted value (PRED) and z residual are listed in the right hand side of the regression run summary.
K-S Analysis of Residuals:	To bring out serious departures from normality, a normal probability plot and a detrended normal plot of residuals were used together with the Kolgomorov-Smirnov test. The statistic, the degrees of freedom (DF) and the significance of the K-S test are included in the table.

Since the experiment was designed with compaction level as a surrogate variable for percent air voids, two sets of regression equations were determined for each of the dependent variables. The first set included compaction as one of the independent variables and percent air voids was removed as an independent variable. The second set included percent air voids as one of the independent variables and compaction was not considered a potential independent variable.

The summary runs for all Y variables are included as tables 47 through 68. (Note some variable names in the tables differ slightly from those in the equations below; also power functions of variables are assigned distinct variable names in the tables, e.g., $[\%ASPHDEV]^2$ = ASCT2 and $[\%ASPHDEC]^4$ = ASCT4TH.) In general, the equations using compaction rather than air voids produce better R^2 and smaller standard errors of estimate. The equations for the first set of regression models are as follows:

$$\ln(MR) = 3.77964 + 1.01907(COMP1) + 1.47333(COMP2) + 0.0013926(\%\#200)(\%\#30) - 0.36999(COMP2)(\%ASPHDEV) + 0.16693(\%ASPHDEV) - 0.008569(\%\#30)(ADT) + 0.0001673(AGGTYP)(\%\#30) - 0.03122(\%\#30)(ASHPCT)^4 + 0.93141(ASPHTYP) \quad (47)$$

$$\ln(TS) = 3.28845 + 0.99605(COMP2) + 0.02248(COMP1)(\%\#30) + 0.57712(ASPHTYP) + 0.01679(\%\#200)(\%ASPHDEV) + 0.59649(COMP1) + 0.01429(COMP2)(\%\#30) - 0.21191(COMP2)(\%ASPHDEV) + 0.01674(COMP2)(\%\#200) - 0.26455(COMP1)(ASPHTYP) + 0.004565(\%\#30)(\%ASPHDEV) \quad (48)$$

$$AGMRR = 3.75047 - 1.78052(COMP2) - 1.52846(COMP1) - 0.007766(ASPHTYP)(AGGTYP) \quad (49)$$

$$AGTSR = 1.743 - 2.249(COMP2)(\%ASPHDEV)^4 - 0.0194(COMP1)(\%\#30) + 0.01152(AGGTYP)(\%ASPHDEV)^4 \quad (50)$$

$$TSMR = 0.13751 + 0.02731(VMA) + 0.00428(\%\#30)(ADT) + 0.003049(\%\#30)(\%ASPHDEV) + 0.26968(COMP2)(\%ASPHDEV)^4 - 0.000343(\%\#200)(\%\#30) - 0.009905(ASPHTYP)(VMA) - 0.0000899(AGGTYP)(VMA) \quad (51)$$

$$MTEMP = -0.02238 - 0.00975(ASPHTYP) - 0.000355(\%\#200)(\%ASPHDEV) - 0.000267(\%\#200)(ADITV) \quad (52)$$

$$IRM = 104.397 - 63.161(ADITV) + 30.40579(ASPHTYP)(ADITV) + 19.97233(COMP2)(ADITV) - 29.367(COMP1)(\%ASPHDEV) + 18.151(ADITV)(\%ASPHDEV) - 0.0038(\%\#30)(\%\#200)^2 \quad (53)$$

$$IRS = 100.428 - 1.8589(\%\#30)(ADITV) \quad (54)$$

Table 47. Regression summary table for unconditioned resilient modulus using compaction as an independent variable.

Regression Summary for Run LNMRALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	108	.985	.31246	17	1.611	101.22	-.6989	1.9007	1.88347	Statistic: .0984	DF: 108	Significance: .0119

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	LNMR							5.135	.923	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		3.77964	.08119			46.6	.0000					18	5.74	3.8440	6.083
X_1	COMP 1	1.01907	.08197	.44661	.7823	12.4	.0000	.204	.405	.150					
X_2	COMP 2	1.47333	.06753	.78156	.91065	21.8	.0000	.389	.490	.610					
X_3	F2ØØ#30	.0013926	.000259	.18995	.48907	5.6	.0000	123.4	125.9	.181					
X_4	C2ASPHCT	-.36999	.09349	-.16436	-.37122	-4.0	.0001	.000	.410	-.074					
X_5	ASPHCT	.16693	.05730	.12085	.28230	2.9	.0044	.007	.668	.031					
X_6	G#30ADT	-.008569	.002685	-.10778	-.30681	-3.2	.0019	10.01	11.61	-.077					
X_7	AGTYP3Ø	.0001673	.0000479	.12777	.33291	3.5	.0007	1106.7	702.5	.136					
X_8	G30AC4	-.03122	.009634	-.11667	-.31113	-3.2	.0016	4.939	3.450	-.101					
X_9	ASPHTYP	.93141	.06027	.50667	.84206	15.5	.0000	.491	.502	.521					
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 48. Regression summary table for unconditioned tensile strength using compaction as an independent variable.

Regression Summary for Run LNTSALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	107	.922	.21712	10	6.877	343.9	-1.0704	.412	1.98056	Statistic: .0678	DF: 107	Significance: >.2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	LNTS							<1.299	.739	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		3.28845	.03974			82.7	.0000					84	3.96	5.0331	-4.93
X_1	COMP 2	.99605	.10193	.66144	.70615	9.8	.0000	.393	.491	.724	X5,X2				
X_2	C1GR#30	.02248	.006008	.25906	.35679	3.7	.0003	3.925	8.51	.161	X1,X6				
X_3	ASPHTYP	.57712	.04723	.39227	.78018	12.2	.0000	.486	.502	.381					
X_4	F200ACT	.01679	.005446	.12323	.300009	3.1	.0027	.084	5.423	.115					
X_5	COMP 1	.59649	.13620	.32783	.40808	4.4	.0000	.206	.406	.124					
X_6	C2GR#30	.01429	.004115	.21726	.33410	3.5	.0008	7.991	11.23	.688					
X_7	C2ASPHCT	-.21191	.06335	-.11820	-.32308	-3.3	.0012	.000	.412	-.005					
X_8	C2F#200	.01674	.006215	.10186	.26507	2.7	.0129	2.355	4.496	.538					
X_9	C1ACTYP	-.26455	.10435	-.10926	-.25050	-2.5	.0475	.103	.305	.159					
X_{10}	G#30ACT	.004565	.002274	.08893	.20074	2.0	.0000	.084	14.4	.107					
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 49. Regression summary table for aged resilient modulus using compaction as an independent variable.

Regression Summary for Run AGMRRALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	95	.353	1.13122	3	1.244	10.462	-1.9935	5.9545	1.75124	Statistic: .1490	DF: 95	Significance: .0000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	AGMRR							2.474	1.416	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		3.75047	.21107			17.8	.0000					45	9.705	3.751	5.264
X_1	COMP 2	-1.78052	.26217	-.62343	-.57997	-6.8	.0000	.421	.496	-.438		50	6.925	3.518	3.012
X_2	COMP 1	-1.52846	.31713	-.44226	-.45095	-4.8	.0000	.211	.410	-.166		49	6.653	3.751	2.566
X_3	ASAGTYP	-.007766	.003637	-.17610	-.21841	-2.1	.0354	26.42	32.12	-.204					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 50. Regression summary table for aged tensile strength using compaction as an independent variable.

Regression Summary for Run A G T S R A L C . R E G

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	93	.27457	.5109	3	1.225	10.356	-.8694	2.772	2.15589	Statistic: .1138	DF: 93	Significance: .0047

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
										YX	XX>0.8	RDNUM	Y	PRED	Z RESID
Y	AGTSR							1.581	.590						
CONSTANT		1.743	.09533			18.3	.0000					84	4.515	1.743	5.43
X_1	C2AC4	-2.249	.39646	-.56681	-.5152	-5.7	.0000	.102	.149	-.418					
X_2	C1GR#30	-.0194	.00639	-.2921	-.30661	-3.0	.0031	4.204	8.879	-.105					
X_3	AGTYPAC4	.01152	.00562	.1935	.2124	2.1	.0433	12.962	9.908	.037					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 51. Regression summary table for unconditioned tensile strength to resilient modulus ratio using compaction as an independent variable.

Regression Summary for Run TSMRALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	107	.531	.14845	9	1.484	57.271	-.5887	.5419	1.36331	Statistic: .0900	DF: 107	Significance: .0328

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	TSMR							.477	.209	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		.13751	.08869			1.6	.1242					18	0.117	.7057	-3.965
X_1	VMA	.02731	.004119	.55583	.55448	6.6	.0000	17.78	4.26	.360		7	1.577	1.035	3.65
X_2	G#130ADT	.00428	.001266	.23501	.32170	3.4	.0010	9.822	11.50	.234		6	1.145	.6979	3.012
X_3	G#30ACT	.003049	.001003	.20952	.29221	3.0	.0030	.084	14.39	.193		8	1.141	.7205	2.832
X_4	C2AC4	.26968	.11497	.18738	.22946	2.3	.0210	.095	.146	.044					
X_5	F200#30	-.000343	.000124	-.20396	-.26816	-2.8	.0067	121.2	124.4	-.255					
X_6	ASTYPVMA	-.009905	.00157	-.44845	-.53450	-6.3	.0000	8.72	9.48	-.337					
X_7	AGTYPVMA	-.0000899	.0000334	-.19566	-.26153	-2.7	.0082	957.4	455.8	-.124					
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 52. Regression summary table for slope of resilient modulus vs. temperature using compaction as an independent variable.

Regression Summary for Run MTEMPALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	98	.4233	.0064	3	1.001	9.009	-.0384	.0204	2.02180	Statistic: .1367	DF: 98	Significance: .0001

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	MTEMP							-.28	.008	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		-.02238	.001014			-22.1	.0000					18	-0.064	-.0256	-6.02
X_1	ASPHTYP	-.00975	.00129	-.593	-.615	-7.6	.0000	.500	.503	-.583		46	-0.059	-.0385	-3.21
X_2	F200ACT	-.000355	.000116	-.239	-.300	-3.0	.0030	.230	5.572	-.221		80	-0.002	-.0224	3.19
X_3	F200ADT	-.000267	.000129	-.163	-.209	-2.1	.0407	3.306	5.033	-.144					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 53. Regression summary table index of retained modulus using compaction as an independent variable.

Regression Summary for Run I R M A L C . R E G

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	97	.4859	26.53	6	2.22	51.96	-48.03	90.38	1.57992	Statistic: .0728	DF: 97	Significance: .2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	IRM							82.17	35.82	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		104.397	4.3005			24.3	.000					56	217	126.42	3.407
X_1	ADITV	-63.161	8.079	-.880	-.636	-7.8	.000	.44	.449	-.530					
X_2	ASTYPADT	30.40579	8.15107	.363	.366	3.7	.0003	.237	.428	-.128					
X_3	C2ADITV	19.97233	8.1483	.227	.250	2.5	.0162	.206	.407	-.152					
X_4	C1ASPHCT	-29.367	9.151	-.259	-.320	-3.2	.0018	.008	.316	-.146					
X_5	ADTACT	18.151	6.562	.223	.280	2.8	.0069	-.008	.440	.150					
X_6	G30SQ200	-.0038	.0018	-.162	-.161	-2.1	.0353	1377	1545	-.180					
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
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X_i = Independent Variable

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T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 54. Regression summary table for index of retained strength using compaction as an independent variable.

Regression Summary for Run IRSALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	96	.2125	40.78	1	1.0	1.0	-62.13	230.27	2.073	Statistic: .2125	DF: 96	Significance: .0000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	IRS							84.12	45.72	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		100.428	5.273			19.0	.0000					104	331	100.4	5.646
X_1	G#30ADT	-1.8589	.3691	-.461	-.461	-5.0	.0000	8.771	11.336	-.461		84	301	100.4	4.925
X_2															
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 55. Regression summary table for aged resilient modulus at 0 °F (-18 °C) using compaction as an independent variable.

Regression Summary for Run AMRØFALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	86	.1832	.246	2	1.34	5.362	-.519	.829	2.03629	Statistic: .0830	DF: 86	Significance: .2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
										YX	XX>0.8	RDNUM	Y	PRED	Z RESID
Y	AGMRROF							.974	.269						
CONSTANT		1.0497	.03727			28	.0000					46	1.924	1.0947	3.369
X_1	ASTYPVMA	-.01382	.00323	-.492	-4.25	-4.3	.0000	9.237	9.578	-.340					
X_2	ASTYP200	.01637	.00627	.300	.276	2.6	.0106	3.140	4.933	.052					
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 56. Regression summary table for unconditioned tensile strength ratio of wet samples at 0 °F (-18 °C) ratio using compaction as an independent variable.

Regression Summary for Run TWRØFALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	97	.385	39.345	4	1.499	20.097	-70.678	171.151	1.70272	Statistic: .1305	DF: 97	Significance: .0003

	VARIABLES	B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	T SWETROF							112.6	49.1	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		1.39936	21.05765			.066	.9472					33	362	190.45	4.35
X_1	ASTP2ØØ	2.43644	.92958	.24339	.26359	2.6	.0103	3.16	4.91	.319		90	298	194.19	2.64
X_2	VMA	5.75531	1.04998	.49284	.49617	5.5	.0000	17.9	4.21	.284		35	218	115.9	2.59
X_3	ADTVMA	-1.66184	.43689	-3.1499	-.36864	-3.8	.0003	8.513	9.309	-.269					
X_4	AGTYP2ØØ	.04243	.01345	.31588	.31248	3.2	.0022	344.5	365.6	.262					
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 57. Regression summary table for resilient modulus ratio of saturated samples at 77 °F (25 °C) using compaction as an independent variable.

Regression Summary for Run MRSATALC . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	107	.1355	32.86	2	1.004	4.017	-90.26	116.54	1.186	Statistic: .1031	DF: 107	Significance: .0070

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
										YX	XX>0.8	RDNUM	Y	PRED	Z RESID
Y	MRSATR							11.75	35.01						
CONSTANT		101.66	5.08			20.01	.0000					7	218	101.7	3.55
X_1	ASTYPVMA	1.167	.335	3.19	.318	3.5	.0007	.486	.502	.300		5	240	137.9	3.10
X_2	C2VMA	.971	.430	.206	.216	2.5	.0259	5.75	7.44	.186		18	11	101.7	-2.74
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 58. Regression summary table for unconditioned resilient modulus using air voids as an independent variable.

Regression Summary for Run LNMRALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	108	.6664	.54619	5	1.139	27.143	-2.5664	1.8396	1.87496	Statistic: .0672	DF: 108	Significance: >.2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
										YX	XX>0.8	RDNUM	Y	PRED	Z RESID
Y	LNMR							5.135	.923						
CONSTANT		5.31538	.14649			36.3	.0000					15	3.05	5.620	-4.699
X_1	ASPHTYP	1.05949	.10559	.57635	.70480	10.0	.0000	.491	.502	.521		13	6.38	4.54	3.368
X_2	AIR1	-.13098	.01265	-.63171	-.71577	-10.4	.0000	8.073	4.453	-.508		18	5.74	4.125	2.965
X_3	F200#30	.0011745	.000434	.16020	.25857	2.703	.0080	123.4	125.9	.181					
X_4	AGTYPCT	-.004455	.0013803	-.19573	-.3044	-3.2	.0017	.007	.464	.020					
X_5	AGTYP30	.0001943	.00007795	.14840	.2396	2.5	.0143	1106.7	705.1	.136					
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 59. Regression summary table for unconditioned tensile strength using air voids as an independent variable.

Regression Summary for Run LNTSALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	107	.5825	.48194	2	1.009	4.035	-1.7318	2.1395	1.90805	Statistic: .0732	DF: 107	Significance: .1988

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	LNTS							4.299	.739	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		4.68051	.08657			54.1	.0000					13	5.37	3.2311	4.439
X_1	A1VMA	.004245	.0004142	-.65219	-.64933	-10.2	.0000	157.4	113.5	-.609		15	2.79	4.523	-3.593
X_2	ASTYP3Ø	.03003	.004135	.46213	.46010	7.3	.0000	9.54	113.7	.401		5	5.56	4.1054	3.014
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 60. Regression summary table for aged resilient modulus using air voids as an independent variable.

Regression Summary for Run AGMRRALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	95	.30287	1.19542	2	1.001	4.004	-1.6353	6.6160	1.61423	Statistic: .1922	DF: 95	Significance: .0000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	AGMRR							2.474	1.416	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		1.48385	.2623			5.65	.0000					45	9.705	3.0890	5.5345
X_1	AIR3	.15892	.02706	.51157	.52224	5.9	.0000	7.84	4.559	.505		50	6.925	3.1003	3.199
X_2	ASAGTYP	-.009688	.003841	-.21970	-.25435	-2.5	.0134	26.42	32.12	-.204		49	6.653	2.9936	3.061
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 61. Regression summary table for aged tensile strength using air voids as an independent variable.

Regression Summary for Run AGTSRALV . REG

EQ	N	R^2	SSE.	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	93	.10113	.562	1	1.000	1.000	-.9927	3.1672	2.02346	Statistic: .1365	DF: 93	Significance: .0002

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	AGTSR							1.581	.590	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		1.3333	.09699			13.7	.000					84	4.515	1.348	5.632
X_1	A4VMA	.001604	.0005013	.3180	.3180	3.2	.0019	154.6	116.97	.318					
X_2															
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 62. Regression summary table for tensile strength to resilient modulus ratio using air voids as an independent variable.

Regression Summary for Run TSMRALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	108	0.505	0.1517	7	11.03	145.73	-0.5775	0.6483	1.03878	Statistic: 0.1237	DF: 106	Significance: 0.0004

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	TSMR							0.477	0.210	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		-0.07792	0.07536			-1.03	0.3037					7	1.577	0.9290	4.2739
X_1	VMA	0.04947	0.006228	1.00562	0.62195	7.94	.0000	17.752	4.277	0.363		18	0.117	0.6941	-3.8072
X_2	AIR12	-0.03469	0.007141	-0.75469	-0.43696	-4.86	.0000	8.041	4.577	0.076		8	1.141	0.5785	3.7062
X_3	ASTYPVMA	-0.01847	0.004681	-0.83321	-0.36703	-3.95	.0001	8.806	9.490	-0.341		6	1.145	0.7178	2.8132
X_4	G#30ADT	0.0039105	0.0012602	0.21868	0.29637	3.10	.0025	10.31	11.77	0.229					
X_5	A12ACTYP	0.01890	0.0092459	0.47750	0.20023	2.04	0.0436	4.138	5.316	-0.285					
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 63. Regression summary table for slope of resilient modulus vs. temperature using air voids as an independent variable.

Regression Summary for Run MTEMPALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	98	.4223	.0064	3	1.001	9.009	-.0384	.0204	2.02180	Statistic: .1367	DF: 98	Significance: .0001

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	MTEMP							-.028	.008	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		-.02238	.001014			-22.1	.0000					18	-0.064	-.0256	-6.02
X_1	ASPHTYP	-.009755	.00129	-.593	-.6150	-7.6	.0000	.500	.503	-.583		46	-0.059	-.0385	-3.21
X_2	F2ØØACT	-.000355	.00163	-.239	-.2999	-3.0	.0030	.230	5.57	-.221		80	-0.002	-.0224	3.19
X_3	F2ØØADT	-.000267	.00129	-.163	-.2093	-2.1	.0407	3.31	5.03	-.144					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 64. Regression summary table for index of retained modulus using air voids as an independent variable.

Regression Summary for Run IRMALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	97	.380	28.6494	3	1.649	12.893	-47.43	112.33	1.50631	Statistic: .0901	DF: 97	Significance: .0503

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	IRM							82.17	35.8	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		109.03643	6.00053			18.2	.0000					56	217	104.47	3.921
X_1	ADITV	-51.7136	7.51953	-.72089	-.5806	-6.9	.0000	.443	.499	-.530		8	165	76.36	3.077
X_2	ASTYPADT	27.10030	8.76726	.32344	.3052	3.1	.0026	.237	.428	-.128					
X_3	AGTYP30	-.008961	.0040788	-.17983	-.22213	-2.2	.0305	1156.6	718.8	-.222					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 65. Regression summary table for the index of retained strength using air voids as an independent variable.

Regression Summary for Run IRSALV.REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	96	.287	39.2256	3	1.471	11.824	-54.74	206.27	2.09085	Statistic: .1664	DF: 96	Significance: .0000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	IRS							84.12	45.72	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		97.97795	5.13856			19.1	.0000					104	331	1234.43	5.259
X_1	G#3ØADT	-1.85097	.35516	-.45900	-.4774	-5.2	.0033	8.77	11.34	-.461		84	301	97.98	5.1834
X_2	A7ASPHCT	-2.35107	.78049	-.32149	-.2996	-3.0	.0231	-1.18	6.25	-.174		73	178	74.89	2.6363
X_3	ADTACT	25.14791	10.88431	.24667	.2342	2.3	.0000	-.016	.448	.079					
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 66. Regression summary table for aged resilient modulus at 0 °F (-18 °C) using air voids as an independent variable.

Regression Summary for Run AMRØFALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K-S Analysis of Residuals		
1	86	.1832	.24613	2	1.340	5.362	-.5188	.8293	1.88174	Statistic: .0830	DF: 86	Significance: >.2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	AGMRROF							.974	.269	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		1.0498	.03727			28.2	.0000					46	1.924	1.0947	3.3695
X_1	ASTYPVMA	-.01382	.003227	-.49176	-.42533	-4.3	.0000	9.237	9.578	-.340					
X_2	ASTYP2ØØ	.01637	.006266	.30017	.27574	2.6	.0106	334.9	359.0	.230					
X_3															
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 67. Regression summary table for tensile strength ratio of wet samples at 0 °F (-18 °C) using air voids as an independent variable.

Regression Summary for Run TWRØFALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	97	.55174	34.34	12	3.220	128.98	-63.62	103.27	1.55479	Statistic: .0704	DF: 97	Significance: .2000

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	TSWETROF							112.6	49.11	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		82.75	6.9072			12.0	.0000					33	362	258.3	3.0069
X_1	A1ØF#200	.34679	.10318	.41283	.33729	3.4	.0012	51.42	58.47	.400		35	218	115.3	2.987
X_2	ADTACT	34.0825	9.70183	.31854	.35070	3.5	.0007	.015	.459	.108					
X_3	A1ØASPCT	-1.6449	.71794	-.21061	-.2373	-2.3	.0243	-.779	6.288	-.181					
X_4	A1ØGR#30	.18265	.03304	.49334	.5077	5.5	.0000	170.2	132.7	.355					
X_5	A1ØADITV	-4.06396	.75493	-.4303	-.4977	-5.4	.0000	4.045	5.20	-.211					
X_6	F2ØØ#3Ø	-.20621	.05101	-.5177	-.3958	-4.0	.0001	119.6	123.3	.210					
X_7	ASTYP2ØØ	2.80247	.84894	.27995	.3320	3.3	.0014	3.155	4.91	.319					
X_8	F2ØØAC4	7.2732	3.23986	.25018	.2327	2.2	.0273	1.566	1.689	.273					
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

Table 68. Regression summary table for resilient modulus ratio of saturated samples at 77 °F (25 °C) using air voids as an independent variable.

Regression Summary for Run MRSATALV . REG

EQ	N	R^2	SSE	STEP	Cond BDS		Min Res	Max Res	DURBIN	K - S Analysis of Residuals		
1	107	.09304	33.5	1	1.000	1.000	-96.282	113.280	1.8608	Statistic: .1305	DF: 107	Significance: .0001

VARIABLES		B	SEB	Beta	Partial	T	Sig	Mean	SD	CORR		Z RESID OUTSIDE ± 2.5			
Y	MRSATR							117.5	35.011	YX	XX>0.8	RDNUM	Y	PRED	Z RESID
CONSTANT		107.682	4.40907			24.4	.0000					5	240	126.6	3.381
X_1	ASTYPVMA	1.11733	.34044	.30503	.30503	3.3	.0014	8.788	9.558	.305		7	218	107.682	3.299
X_2												18	11	107.68	-2.874
X_3												8	218	130.53	2.596
X_4															
X_5															
X_6															
X_7															
X_8															
X_9															
X_{10}															
X_{11}															
X_{12}															

EQ = Equation number for a regression file
N = Number of valid cases
R^2 = Coefficient of Determination
SSE = Standard Error of Estimate
STEP = Number of steps to reach R^2
Cond BDS = Condition Boundaries
Min Res = Minimum Residual
Max Res = Maximum Residual
DURBIN = Durbin-Watson Test statistic
K-S = Kolmogorov-Smirnov Test
DF = Degrees of Freedom
Y = Dependent Variable
X_i = Independent Variable

B = Unstandardized regression coefficient
SEB = Standard error of B
Beta = Standardized regression coefficient
Partial = Partial Correlation Coefficient
T = t-value for the Test of B
Sig = Significance of the t-value
Mean = Mean value for the dependent or independent variable
SD = Standard Deviation
CORR = Correlation coefficients
YX = Correlation coefficients between the independent and dependent variable

XX = Correlation coefficient between independent variables
RDNUM = Test cell identification number
Y = Value of he dependent variable corresponding to RDNUM
PRED = Unstandardized predicted value corresponding to RDNUM
ZRESID = Standardized residuals corresponding to RDNUM

AGMRROF = 1.0497 - 0.01382(ASPHTYP)(VMA) + 0.01637(ASPHTYP)(%#200) (55)

TSWETROF = 1.39936 + 2.43644(ASPHTYP)(%#200) + 5.75531(VMA) - 1.66184(ADITV)(VMA) + 0.04243(AGGTYP)(%#200) (56)

MRSATR = 101.66 + 1.167(ASPHTYP)(VMA) + 0.971(COMP2)(VMA) (57)

The COMP1 and COMP2 values are defined as:

	COMPACTION		
	HIGH	MEDIUM	LOW
COMP1	0	1	0
COMP2	1	0	0

The equations for the second set of regression models are as follows.

ln(MR) = 5.31538 + 1.05949(ASPHTYP) - 0.13098(%AIR) + 0.0011745(%#200)(%#30) - 0.004455(AGGTYP)(%ASPHDEV) + 0.0001943(AGGTYP)(%#30) (58)

ln(TS) = 4.68051 + 0.004245(%AIR)(VMA) + 0.03003(ASPHTYP)(%#30) (59)

AGMRR = 1.48385 + 0.159892(%AIR) - 0.009688(ASPHTYP)(AGGTYP) (60)

AGTSR = 1.3333 + 0.001604(%AIR)(VMA) (61)

TSMR = -0.07792 + 0.04947(VMA) - 0.03469(%AIR) - 0.01847(ASPHTYP)(VMA) + 0.0039105(%#30)(ADITV) + 0.01890(%AIR)(ASPHTYP) (62)

MTEMP = 0.02238 - 0.009755(ASPHTYP) - 0.000355(%#200)(%ASPHDEV) - 0.000267(%#200)(ADITV) (63)

IRM = 109.03643 - 51.7136(ADITV) + 27.10030(ASPHTYP)(ADITV) - 0.0008961(AGGTYP)(%#30) (64)

IRS = 97.97795 - 1.85097(%#30)(ADITV) - 2.35107(%AIR)(%ASPHDEV) + 25.14791(ADITV)(%ASPHDEV) (65)

AGMRROF = 1.0498 - 0.01382(ASPHTYP)(VMA) + 0.01637(ASPHTYP)(%#200) (66)

TSWETROF = 82.75 + 0.34679(%AIR)(%#200) +

$$34.0825(ADITV)(\%ASPHDEV) - 1.6449(\%AIR)(\%ASPHDEV) + 0.18265(\%AIR)(\%\#30) - 4.06396(\%AIR)(ADITV) - 0.20621(\%\#200)(\%\#30) + 2.80247(ASHPTYP)(\%\#200) + 7.2732(\%\#200)(\%ASPHDEV)^4 \tag{67}$$

$$MRSATR = 107.682 + 1.11733(ASPHTYP)(VMA) \tag{68}$$

All of these equations were produced during the development of the prediction equations presented in the main body of the report. They are included here for the benefit of those who wish to review the analysis process. The rationale for the final selection of prediction equations will be found in the appropriate sections of the main body of the report.

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